TEXTBOOK OF THE MATERIALS OF ENGINEERING

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With a chapter on COHESION, STRESS, AND STRAIN
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A chapter on CONCRETE
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And a chapter on PLASTICS
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PREFACE TO THE FIRST EDITION

The object of this textbook is to furnish a concise presentation of the physical properties of the common materials used in structures and machines, together with brief descriptions of their manufacture and fabrication. The book is intended primarily for use in technical schools in connection with courses in the mechanics of materials, or in connection with courses in the materials testing laboratory. It is hoped, however, that the book may prove to be of use to draftsmen, inspectors, machinists, and others who, dealing with the materials of engineering in their daily work, wish to become familiar in an elementary way with the properties of those materials.

The text is distinctly elementary in character, and for the reader who may wish to pursue his studies further there is given at the end of each chapter a list of selected references. The books and periodicals named in these lists will be found in nearly all technical school libraries, and in many city libraries. For the convenience of teachers who may use this book as a text, a list of questions on the various chapters is given at the end of the last chapter.

This work is, of necessity, a compilation of data from various sources, and the author has endeavored to give credit where it is due. He acknowledges his indebtedness to the references given in the lists and to the various individuals who have assisted him.

Herbert F. Moore

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CHAPTER I

INTRODUCTORY

Scope of This Book. Whenever a structural or a machine part is to be designed it is necessary to consider various factors in the problem. Among these factors *three* are almost always of major importance: (1) What forces and moments will the part be required to withstand? (2) What shall be the form and dimensions of the part so that it may function properly without failure? (3) What material will be the best to use, considering resistance to fracture, collapse, or change of form? Cost, and frequently appearance, must also be considered.

Factors 1 and 2 are somewhat interdependent, and the methods and formulas of applied mechanics may be used in their study, *if the limitations of those formulas are recognized.* This book concerns itself mainly with the third factor—the properties of structural materials that enable them to offer successful resistance to structural damage[1] by applied moments and forces.

General Properties of Materials: Strength. In some structures and machines the strength of the materials used is the prime requirement, while in other structural or machine parts some other factor (such as weight, color, electrical conductivity) may govern the selection of the materials. However, in all machines and structures the materials used must have sufficient strength to prevent the actual fracture or collapse of parts with the consequent failure of the structure. The strength of a material is a measure of its ability to resist the application of the load required during the service of the structure or machine without fracture, collapse, or undue distortion.

The application of load or moment to a part of a structure or a machine causes internal balancing forces and moments to be set up of that part. The intensity of such internal force is called *stress,* and it is measured in pounds per square inch. There are three kinds of stress commonly used in structural and machine design: *tension*, *compression*, and *shear*. Figure 1 illustrates these three types of stress.[2]

[1] Some writers limit the term "structural damage" to the weakening of the material as shown by tests of specimens, and they use the term "functional damage" for damage of a structural or machine part sufficient to cause that part to function poorly or incorrectly. In this book the term "structural damage" is applied both to the material and to the parts made of that material.

[2] In some engineering texts an internal force (measured in pounds or in kilograms)

Flexure, or bending stress, is a combination of tension and compression with some shear. Bearing stress (*e.g.*, the stress in the rail under a railway car wheel) is a complex combination of compression, shear, and and some tension.[1] Under torsion (*e.g.*, a shaft transmitting power) the shearing stresses are very important and there are tensile and compressive stresses equal to the shearing stresses.

Any stress is accompanied by a deformation—stretching, compressing, or shearing—or by a combination of the three. The resulting change of

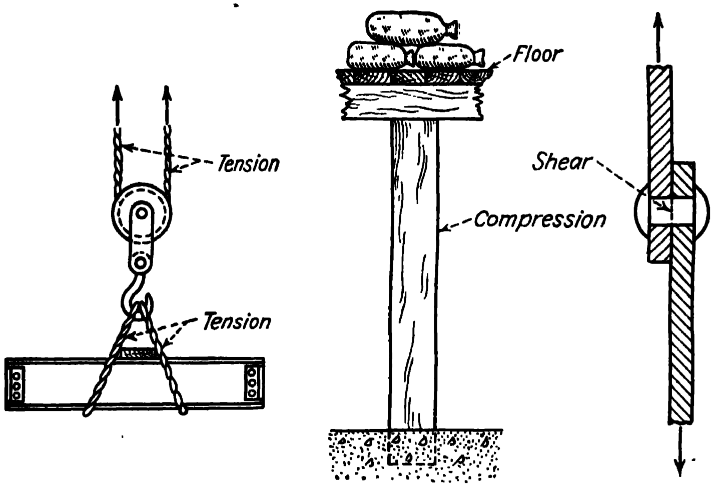

FIG. 1. Illustrations of tensile, compressive, and shearing stress.

length per unit of length in a linear dimension of a body is called *strain*, and is measured in inches per inch, centimeters per centimeter, or by percentage of change of dimension.

Stiffness. Stiffness and strength of materials are sometimes confused; they are, however, two distinct properties. If the stress is set up in a part of a machine or a structure the form of that part is slightly changed. This change of form is called *deformation*, and a material which suffers

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is called *stress* and intensity of internal force (measured in pounds per square inch or kilograms per square millimeter) is called *unit stress*. In this book the intensity of internal forces (pounds per square inch) is called *stress*, following the nomenclature of the American Society for Testing Materials as given in its 1949 "Standards," Part 1, p. 1228.

[1] There is a combination of more than one type of stress at any location in a structural or machine part. Moreover, the most generally accepted theory of strength of materials is that, for nonbrittle materials at least, what tends to cause damage is not *stress* by itself, but a combination of stress and deformation (strain), a *strain* energy. This matter is discussed on p. 29.

only slight change of form under stress has a high degree of *stiffness.* Stiffness is frequently a very important property of a material. For example, in a machine tool there should be very slight deflection of parts under normal conditions of working, else the machine tool will fail to produce work of a sufficient degree of precision. In this case material of high stiffness is desirable. On the other hand, it is desirable that railway ties should yield under load so as to minimize shock, and for this service a material with a low degree of stiffness, such as timber, is preferable to one with a high degree of stiffness.

Elasticity and Plasticity. Materials under low stresses do not suffer any appreciable permanent change of form, recovering their original form after the removal of load. Under such conditions they are said to be *elastic.*[1] Under high stresses materials do suffer a permanent change of form, and become somewhat *plastic.* A plastic material does not recover its shape after removal of load, reaching equilibrium after a certain amount of distortion. It does not change form continuously as long as load is applied, as does a viscous liquid. Under increasing load the change from a state of nearly perfect elasticity to one of a considerable degree of plasticity takes place suddenly for some materials, especially steel, wrought iron, and some rolled or hammered metals; such metals are said to have a well-defined *yield point.* Other materials, such as timber, concrete, and cast iron, show a mixture of elastic and plastic action even under low loads, but do not exhibit nearly so great a degree of plastic action at high loads as do the materials noted above.

Flow of Materials. Under elevated temperatures many materials show signs of *flow,* acting like a viscous liquid. Unlike plastic action, flow continues as long as load is applied Some materials, such as lead and sealing wax, show signs of flow at ordinary room temperatures. Flow of a material is usually called *creep,* on account of its slow action. It is doubtful whether any sharp limit of load or stress can be established, below which flow (creep) is zero. However, limits of load or of stress and temperature can be determined by test, and below these limits the magnitude of flow (creep) is not sufficient to cause any appreciable structural damage.

Toughness and Brittleness. Some materials will withstand great deformation together with high stress without fracture. Such materials have great *toughness.* Other metals shatter before much strain has

[1] It is doubtful whether any structural material is *perfectly* elastic under any stress. However, under working stresses the plastic action is not measurable except by the use of strain-measuring instruments of extreme sensitivity, or by the dying out of vibrations set up in the material. Such slight plastic action rarely causes structural damage except under loads repeated thousands or millions of times.

TABLE I. DESIRABLE PROPERTIES FOR MATERIALS

By permission of Professor J. O. Draffin, University of Illinois

Property	Examples of need of property
A. Properties related to durability and continued usefulness in service	
Resistance to fracture	Cable for suspension bridge; chain link
Resistance to crushing, shearing or buckling	Bridge pier; web of railroad rail
Resistance to repeated load	Live (rotating) axle; deep-well pump rod
Absorption of energy	Spring; rubber tire
Minimum damage by notches, holes, keyways, etc.	Threaded bolts under repeated tension; shaft with small radius of fillet at shoulder
Resistance to elastic deformation (elastic stiffness)	Milling machine shaft; long, thin column
Constancy of grain size	Precision standard of length; furnace grates
Low coefficient of expansion with temperature	Length-measuring instruments; paving blocks
Resistance to "creep" under long-continued load	Bolts in steam lines; lead sheathing for electric cables
Resistance to indentation	Ball-bearing races; railroad rails
Resistance to wear or abrasion	Bearings; linoleum floor coverings
Resistance to corrosion	Roof gutters; jet-engine parts
B. Properties related to suitability for certain functions	
Light weight	Airplane parts; life preservers
Transmission of light	Window glass; lenses
Transmission of heat	Boiler tubes; electric iron
Lack of transmission of heat	Refrigerators; concrete blocks
Absorption of sound	Auditorium walls; silencer on motor exhaust
Resistance to high-frequency radiation	Lead walls; thick blocks of concrete
Magnetic properties	Electric generator; surveyor's compass
C. Properties affecting the fabrication of materials	
Easy casting of molten metal	Cooking stove parts; memorial tablets
Ability to be molded	Powdered metal; ceramic products; plastics
Ability to be deformed without fracture	Concrete reinforcing bars; tooth-paste tubes
Ability to be welded	Pipes; structural parts of bridges

taken place; such materials are *brittle*. In Table I, which examples require a tough material[1] and which can use a brittle material?

Toughness is a highly desirable quality for structural and machine

[1] In connection with toughness it is again to be noted that stress is always accompanied by strain. In this book the term *toughness* is to be used as a measure of the stress-strain *energy* required to fracture a metal. Some writers on materials use the term *resilience* to denote what in this book is called toughness. The writers of this book define *resilience* as the energy which can be *recovered* on the release of stress.

parts which have to resist occasional high loads or heavy shocks as a result of which, even if the part is not fractured completely, it may have a crack started that will reduce its resistance to subsequent heavy shocks or loads. Look over Table I and ask yourself which of the examples listed especially requires toughness in the material.

Ductility and Malleability. Some materials under tension can be drawn out to a considerable elongation without fracture; such materials are *ductile*. A ductile material which can be stretched out only under high stress is *tough*. A material which can be hammered into thin sheets is *malleable*. Lead is malleable and ductile, but not tough. The significance of ductility is discussed on page 26.

Uniformity and Reliability. Some materials can be produced with a high degree of uniformity of properties, such as strength, stiffness, etc., while the properties of other materials cannot be foretold within wide limits. For engineering work material which is uniform in quality is always desirable. Materials whose structure is continuous throughout resist repeated stress better than materials with discontinuities, such as cracks. Under the action of repeated stress, minute cracks are liable to start at points of discontinuity, and the material is sometimes fractured by the spread of these minute cracks.

Hardness. Hardness is a term used to designate several different properties of a material—resistance to abrasion, to cutting, to indentation, or to wear. All these involve complex stresses and deformation. No one definition covers the uses of the term hardness.

Durability. It is desirable that during the period of use of any structure or machine the material in it should not deteriorate in quality. Destructive agencies not infrequently act on the materials of construction; *e.g.*, corrosion attacks steel and iron, bacterial growths cause wood to decay, electrolytic action sometimes destroys concrete. Mechanical wear of parts may destroy the usefulness of a machine. For any given construction the durability of the materials to be used must be considered.

Tests of Materials. *Chemical Tests.* Chemical analyses of materials whose quality is under investigation are usually made on small representative samples of the material and have for their chief object the determination of the quantity of various ingredients present in the material. They are frequently used to detect the presence of an injurious amount of an undesirable ingredient, or to detect unevenness of distribution of ingredients through a mass of material (segregation).

Mechanical Tests. The mechanical tests commonly performed to determine the quality of materials of construction include tests of strength (tension, compression, shear, bending, torsion), of ductility (elongation, bending), of brittleness (impact tests), of resistance to repeated stress

(fatigue tests), of hardness, of resistance to abrasion, and of the internal structure (microscopic examination). Mechanical tests are made, usually on a small sample of the material but sometimes on the material in its finished form. Mechanical tests may be tests to destruction (*e.g.*, a tension test to rupture of a small test piece made from a sample taken from a shipment of steel) or tests under working load (*e.g.*, a test of the floor of a building under the load it is supposed to carry in service). In general, laboratory tests to destruction do not tell directly whether a material is the proper one for a particular use, but only whether it has physical properties similar or superior to those of some other material which has given good service.

Usable Strength and Structural Damage. The extreme usable strength of a material for any service is commonly measured by the smallest stress which causes *structural damage.* However (see footnote, page 24), structural damage means deformation, flow, or fracture so great that the part made of the material fails to function properly. For example, a ductile steel in a warehouse column is permanently deformed by an excessive load—so greatly deformed that the column is no longer able to carry its load without danger of collapse. The member has failed and must be replaced. However, in the same building slight permanent deformation may have occurred over hundreds of minute areas (around rivet holes, for example) but these localized distortions do not constitute structural damage because the columns and beams still function properly. On the other hand, such local distortions, repeated thousands of times by repeated loading, might start spreading cracks which would eventually cause disastrous fractures. In the case of the statically loaded warehouse, *localized* overstress is not to be regarded as structural damage, while in a machine part subjected to thousands of cycles of loading, localized overstress is to be regarded as structural damage—at least as potential structural damage.

Service conditions may be classified in various ways. One way is to classify them by type of loading (static, repeated, or impact). A second way is classification by kind of stress (tension, compression, shear). A third classification is by temperature (very cold, room temperature, temperature at which the material will "creep").

Nearly all the tests described and the data presented in this book are the results of tests of specimens of *material,* made by testing engineers under laboratory conditions. These results show the maximum values of stress, strain, or strain energy which the material is able to withstand. These results cannot be used *directly* for designing of structural or machine parts made of the material tested. In making a machine or structural part out of a given material the shape, size, surface condition, and freedom

from sharp discontinuities (stress-raisers) frequently make the allowable stress considerably below that indicated by tests of smooth polished specimens. On the other hand, the surface of the part may be so treated (*e.g.*, by shot-peening) that the strength is increased. However, in general the *safe working stress* for a structural or machine part is *less* than the safe working stress based directly on tests of specimens of the material. This subject is discussed more fully in Chap. VII.

Selected Reference for Further Study

KIPLING, RUDYARD: "The Day's Work," Doubleday and McClure Co., New York. In this book are three short stories, "The Bridge Builders," "The Ship That Found Herself," and "Bread upon the Waters," which will give the student of materials a vivid picture from a nontechnical viewpoint. Note the outlining of the modern theory of "fatigue of metals" in "Bread upon the Waters," and the equalization of stress in the ship plates by the slight yielding of the rivets in "The Ship That Found Herself."

Questions

1. In which of the following structural parts is strength the property most important to the designer or user: watch spring, connecting rod of engine, slender column in a steel frame building, lead sheathing on an electric power cable, spindle of a lathe, electric wire for house wiring, electric power transmission wire, wood for interior finish, railroad tie, floor beams of a dwelling house, ornamental concrete railing, concrete pavement, retaining wall, brick veneer walls, drain tile, rubber belting, steering knuckle of an automobile?

2. Name several structural or machine parts in which stiffness is desirable. Name others in which it is not important.

3. Name several structural or machine parts in which localized plastic action is not injurious. Name others in which it is injurious.

4. Distinguish between flow (or creep, as it is sometimes called) and inelastic deformation. Give examples of each.

5. In which of the following structural parts is resistance to creep important: a girder beam in a bridge, a gas-turbine blade, the bolts connecting flange joints in a high-pressure line, the bolts connecting flange joints in a city water line, a concrete retaining wall, the lead sheathing around an electric power cable, a timber beam in a warehouse, a plastic rod in tension, a railroad rail, stay bolts in a locomotive firebox?

6. Would you recommend the use of very hard steel for the floor beams of a highway bridge? Give your reason.

7. Gray cast iron alloyed with nickel, chromium, and other elements has been successfully used for crankshafts of internal-combustion motors. Would you call this alloy strong, tough, ductile, weak, or brittle?

8. What constitutes structural damage to a machine or structural part? Name four types of structural damage. Give examples of each type.

9. When a very long column buckles under load, is the *material* in it necessarily damaged? Explain.

10. Can you add further examples of parts requiring the desirable properties listed in Table I?

11. Can you add desirable properties to those listed in Table I and list examples of parts requiring such properties?

12. In Table I which examples require a *malleable* metal?

CHAPTER II

COHESION, STRESS, AND STRAIN

By Jasper O. Draffin[1]

Cohesion. Cohesion is that property of solid bodies by virtue of which they resist being broken into fragments or ruptured. In an engineering sense the resistance of bodies to fracture is measured by the magnitude of the external force required to cause rupture, and this is usually called the strength. The exact nature of cohesion is unknown, but it is believed to be an atomic phenomenon. In a solid body the atoms are held in a fixed location by a number of balanced forces, some attractive and some repulsive. An atom consists of a nucleus, in which is concentrated nearly all the mass of the atom, and this nucleus is surrounded by a number of electrons revolving in orbits around the nucleus, the electrons being in such rapid action that they form the equivalent of a shell around the nucleus. The net effect of the attractions and repulsions between the nuclei and electrons of a number of atoms is to prevent the actual contact of the nuclei, but yet to hold them in equilibrium while separated from each other. While this is a crude picture of the nature of cohesion, and it may be superseded in the light of further study, it is still serviceable for elementary study.

The actual strengths of solid materials, as given in the tables in Chap. VI, are much less than the sum of the atomic cohesive forces when these latter are determined by measuring the energy required to change solids to liquids. Thus it would seem that only a small portion of the atomic bonds are effective in resisting the force tending to break the solid into fragments. For an explanation of this discrepancy, it is necessary to consider the manner in which atoms are arranged in solids, and this is discussed in Chap. X.

Average Properties of Materials. A piece of material used for a machine or structural part contains millions of crystalline grains or fibers, and each grain and each fiber contains millions of atoms. Where so many units are concerned, it is frequently a satisfactory method of analysis or study to consider the *average* behavior of the units. In the engineering study of strength of materials, a machine or structural part is considered to act as though it were made up of homogeneous material,

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equally stretchable or compressible in all directions (such a material is termed *isotropic*), and capable of being divided and subdivided into indefinitely small units, with each small unit having the same properties as the larger one.

The properties of materials are, in part, compared by means of the numerical values of the strengths and deformation (stresses and strains) which the materials are capable of developing under various types of force systems. The average strength and ductility properties of a material are usually determined by a testing machine which, by means of leverage, screw power, or hydraulic power, applies a force and, by means of a beam balance or some self-indicating weighing device, indicates the amount of force applied. By appropriate methods of computation, which are briefly discussed later, the strengths of the materials are then computed.

In general this average, or statistical, method is satisfactory to the engineer for computing the strength of machine and structural parts. Actually, of course, each such part contains a vast number of more or less isolated grains, so placed that they are unable to resist effectively the forces exerted on them, and so they are at least partially fractured. Yet, unless the part is subjected to many repetitions of load, the total damage to the part due to the fracture of a few such isolated crystalline grains is usually negligible. But if the forces are repeated thousands of times, the microscopic cracks caused by the breaking up of isolated grains sometimes *spread* until they cause the failure of the whole machine or structural part. This action, commonly called "fatigue of metals," is discussed in more detail in Chap. V.

Strain. Whenever a force is applied to any member of a machine or structure—a beam in a house, a gear in an automobile, a railroad rail, a member of a bridge truss—the shape and dimensions of the member are altered, so that it is lengthened, shortened, twisted, or displaced (deflected) from its original position. If the member has been properly designed to withstand the force, the changes of shape and dimension are small, usually not directly visible to the eye, and on removal of the force the member returns almost exactly to its original size and shape. If the force is too large, or the member is improperly designed, then there is considerable change of shape, and if the load is removed the member will *not* return to its original shape and size, but will remain permanently distorted. Structural damage has been done to the member.

The change in any linear dimension of a structural or machine part is called the *deformation*, and the change of deformation per linear unit is called the *strain* (see Chap I, page 2), which may be measured in

inches per inch or by percentage of change of linear dimension. Along with the strain in a longitudinal dimension of a part with load in a longitudinal direction, there are strains in all directions. The lateral strain for each group of metals and for relatively low strains is a fairly constant proportion of the longitudinal strain; it is called Poisson's ratio, and for steel it is not far from 0.25. While this ratio is not much used in the study of the action of materials under the simpler stress conditions, it is an important constant of the material for parts under complex stress conditions.[1]

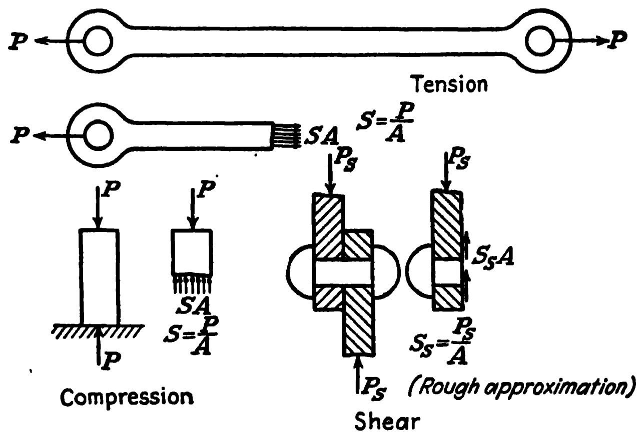

FIG. 2. Uniformly distributed stress.

Direct Stress, Uniformly Distributed. Where a machine part or a structural member, Fig. 2, is acted upon by tension or compressive forces P, P which act along the axis of the member, there are set up within the member internal forces or stresses which resist the tendency of the external forces to tear apart or to crush the member. These internal stresses, computed as explained later, are then compared with the known strengths of the material used in the part, the strengths being determined by tests of specimens of the material. To compute the stresses, imagine the part of the member at one side of any plane section to be cut away; then there will be internal stresses S the summation of which over the

[1] The stresses and strains commonly used neglect many stresses and strains in and between the crystalline grains or fibers of a material. Such stresses and strains may be called *microstresses* and *microstrains*, while the larger-scale stresses commonly used in computation may be called the *nominal* stresses and *nominal* strains. The microstresses cannot be computed by any formulas now known, but the first observed serious structural damage (distortion visible to the unaided eye), such as cracks, etc., nearly always occurs in a region of maximum nominal stress, and when that damage can be measured quantitatively, it seems to bear some direct relation to the nominal stress, although the ratio is not always a linear one.

area of the section will balance the force P. The stress perpendicular to the plane of the section is $S = P/A$, in which P is the resultant force in pounds acting on one side of that section and A is the area of the section in square inches. This formula is used to compute the nominal stress in axially loaded members and also to compute the strengths of a material tested under direct load. However, the formula is rigidly correct only if the stress is *uniformly distributed over the section.* Hence this stress is spoken of as a *nominal* stress. Such a uniform stress distribution is usually assumed for the bodies of eyebars, tie rods, bolts under tension, ropes, guy wires, short posts, bearing blocks, and many other machine and structural parts.

If the loading is carried to failure, the area A of the section is slightly decreased under tension and slightly increased under compression, but usually the nominal stress at failure (ultimate strength) is based on the original area—the area before any load was applied. The justification for the assumption of uniform stress distribution in the design of a member in direct stress lies partly in the fact that, along with this assumption, is the fact that the strengths of the materials used in the member are determined by test, in which they are based on an assumption of uniform stress distribution. Though the assumptions are not exactly true in either case, the variation from the truth is approximately the same in each case, and as a consequence the assumptions are satisfactory, provided there is not too great a variation between the conditions existing in design and in tests.

The stress distribution in long compression members is more complex than in short ones since it involves a combination of axial compression and bending. Consequently, the compressive strength of a *material*, as distinguished from that of a structural or machine *part*, must be determined from the test of a *short* specimen.

For parts subjected to transverse forces whose lines of action are parallel and so close together that there is no appreciable bending action (such as the rivet connecting two plates in Fig. 2), the parts are said to be in *shear*. In parts which are riveted, bolted, or welded together, the magnitude of the nominal shearing stress in the rivet, bolt, or weld is commonly assumed as $S_s = P_s/A$, in which S_s is the nominal shearing stress in pounds per square inch, assumed to be uniform over the surface of the cross section, P_s is the shearing load in pounds, and A is the area of cross section in square inches.

As in tension and compression, this shearing stress is an *average* or nominal shearing stress over the cross section, and this average shearing stress is usually considered to be the maximum shearing stress for rivets, bolts, pins, and welded joints in shear. In addition to the direct shearing

stress, there are also always present heavy *bearing stresses* at points of contact of pins, bolts, or rivets with the plates which they fasten together, with a resultant cutting action at the surface of the pin, bolt, or rivet and an intensified shearing stress. However, since the shearing strength of the material used for this type of stress is determined under similar conditions, with suitable values for the allowable stress, the formula just stated is quite generally used in practice.

Stress Nonuniformly Distributed. In any actual structural or machine part the use of the direct-stress formula, $S = P/A$, neglects many localized stresses, especially near the points of attachment to other parts; *e.g.*, the bearing stresses between an eyebar and the pin to which it is attached. In most actual members there are also some slight irregularities, due to shape, surface finish, small holes; and these *stress raisers*, as they are called, may cause some minute permanent distortion and thus produce high stresses at the irregularity of discontinuity. Figure 3 shows the approximate distribution of stress, determined by formulas of the mathematical theory of elasticity, over the cross section of an axially loaded member containing a notch with a small radius. The height of the ordinates represents the theoretical stress at any point in the cross section. The highly stressed portions *deform* more than the lower-stressed portions under some conditions, and part of this greater deformation is permanent. The ability of the material to distribute the load to the adjacent grains is due to the ductility of the material and can take place to an appreciable degree only where there is considerable ductility, as in soft steel. In materials low in ductility, such as gray cast iron, hard steels, and some copper alloys, there is only a small amount of stress distribution possible, and therefore overloading may result in the fracture of a few grains, which small fracture may progress to the rupture of the entire piece. Were it not for ductility, it is doubtful whether the common method of stress computation could be used in the design of parts for structures and machines, even under static or steady loads. Points of high stress concentration are very undesirable, especially in structural or machine parts subjected to energy or impact loads, in which the magnitudes of the forces applied are sometimes very difficult to determine. Points of high stress concentration are very undesirable indeed in parts subjected to thousands of

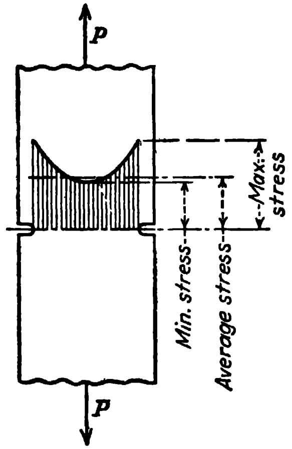

FIG. 3. Stress concentration at a notch in a plate.

cycles of stress. A fuller discussion of the significance of localized stress concentration, particularly for parts subjected to repeated loads, is given in Chap. V.

Stress on an Oblique Plane Due to a Direct Load. In any machine or structural member under an axial load, there are both tensile (or compressive) and shearing stresses on any plane oblique to the load. On such an oblique plane (see Fig. 4) the tensile (or compressive) stress normal to the oblique plane is less than it is on a plane normal to the axis of the piece, while the shearing stress is greater. The shearing stress is a maximum for a plane at an angle of 45 deg. with the axis, and for this plane the shearing stress is $S_s = P/2A$. A piece of ductile steel subjected to tension frequently fails along an oblique plane, as does a cylinder of concrete under compression. Such oblique failures mean that for fracture the material is weaker in shear than it is in tension (or compression of concrete) since, by the equation just stated, the shearing stress under direct load cannot exceed one-half the tensile (or compressive) strength of the material under test.[1] Of course, if it is desired to describe completely the stress system acting on any small volume, the direction as well as the magnitude of each stress must be known.

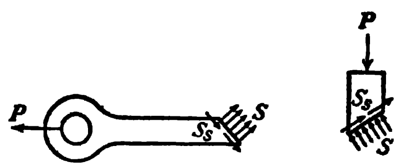

FIG. 4. Stresses on oblique section.

Hooke's Law. Under working conditions, the materials commonly used to carry loads in structures and machines follow very closely *Hooke's law*, which states that *stress is proportional to strain.* This law is named after the English scientist who first stated it, and within limits the ratio is a constant, or very nearly so. This ratio is called the *modulus of elasticity* which, for tensile and compressive stresses, is designated by E and measured in pounds per square inch.[2] The modulus of elasticity is a measure of the elastic stiffness of the material, and the equation for it is $E = S/\epsilon$, in which ϵ is the strain in inches per inch (or in per cent). Hooke's law is based on experimental observation and

[1] Gray cast iron has greater strength for fracture in compression than in shear, and greater strength in shear than in tension. In fact, it is impossible to conceive of fracture under compressive strength alone; about the only load distribution which produces *only* compressive stress is three-dimensional hydraulic pressure which can set up three-directional compressive stress with very large values without fracture, and when fracture does occur under hydraulic pressure, it is probably due to the nonhomogeneity of gray cast iron. Gray cast iron, then, has a higher fracture strength in shear than in tension.

[2] For shearing stresses the corresponding stress-strain ratio is called *modulus of rigidity* and is denoted by G.

is probably a close approximation of the general action under low stresses of appreciable masses of most materials of construction. Average values of E for various materials are given in Table IX, page 86. The laws hold very closely for rolled metals and cast steel, fairly closely for cast metals other than steel, fairly closely for concrete, brick, and wood, and only roughly for rubber, leather, and hemp rope. They hold quite closely for some plastics (see Chap. XVI).

For most materials of construction there is a limiting stress, more or less well defined, above which deviations from Hooke's law can be detected by careful measurements of strain. To this limiting stress the name "proportional limit" has been applied, and above this limit Hooke's law does not hold and the ordinary formulas of mechanics of materials, those which involve the modulus of elasticity in their derivation, are not exact.

The value of the proportional limit determined by tests depends on the sensitivity of the testing machine, the accuracy of measurement of the specimen, and especially on the sensitivity of the strain-measuring apparatus used in the test. A more practical value of the limiting stress for the reliability of Hooke's law and of elastic action in a material is the *yield strength*, which is discussed in Chap. III.

Nonaxial Nonuniform Stress. Under flexure, torsion, or combinations of these and axial loadings, the stress distribution in a structural or machine part is more complex than under axial load alone. On any cross section, the stress may vary from surface to surface, or from axis to surface, and the properties of the material as determined or required under such stress conditions are sometimes different from those determined or required under axial loads. Where the properties of the materials used for a structural or a machine part are determined by nonaxial load tests, the strengths computed by the formulas which follow are sometimes designated as "modulus of rupture" in bending or in torsion. Frequently, however, the properties of the materials used for members under nonaxial load are determined from axial-load tests, and suitable allowances are made for the conditions under which they are used.

The mathematical analysis of stress distribution properly forms the subject matter of mechanics of materials. Therefore, no extended discussion of such stress distribution will be presented in this book; however, two of the common formulas for determining nominal flexural stress in beams and nominal shearing in round shafts are given.

Flexure. In a machine or structural part under cross-bending, or flexure, the external bending moment at any cross section causes an extreme fiber stress which may be computed by the equation $S = Mc/I$, in which S is the maximum tensile stress at the surface if c is measured from the centroidal (neutral) axis of the cross section to the "tension"

TABLE II. COEFFICIENTS OF EXPANSION

The values tabulated are averages of the linear coefficients of expansion per degree Fahrenheit

Material	Coefficient of expansion, in. per in. length per deg. F.	Material	Coefficient of expansion, in. per in. length per deg. F.
Aluminum	0.0000130	Concrete	0.0000055
Brass	0.0000101	Granite	0.0000036
Bronze	0.0000098	Limestone	0.0000028
Copper	0.0000089	Marble	0.0000038
Gray cast iron	0.0000056	Plaster (white)	0.0000092
Steel	0.0000066	Porcelain	0.0000020
Wrought iron	0.0000065	Sandstone	0.0000052
Zinc	0.0000141	Slate	0.0000058
Brick	0.0000031	Wood (parallel to grain)	0.0000025
Brick masonry	0.0000040	Wood (perpendicular to grain)	0.0000230

but if the part *is* restrained from free expansion or contraction under the application of heat, a stress is set up in the member. This stress S will be equal to $E\epsilon$, in which E is the modulus of elasticity, and ϵ is the expansion or contraction per inch of length which would have occurred but was prevented by the restraint on the material.

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Questions

1. Give a verbal picture of cohesion in a solid body in terms of attractions and repulsions between atoms and parts of atoms.

2. In actual materials, is the full strength of all atomic attractions and repulsions developed? Explain.

3. Explain what is meant by the statement that the ordinary formulas of mechanics of materials are not rigorously true when applied to stresses and strains in machine and structural parts, but that those formulas may be regarded as *statistically* true.

4. The ordinary formula for the deflection of a beam under a load at midspan gives results very close to those found by actual test. The formulas for stress and strain in a minute region give results that frequently differ materially from those found by tests to failure. Why is there excellent agreement in the case of the beam and poor agreement in the case of the minute area of high stress?

5. Define stress, strain. In what units is each measured?

6. An aluminum alloy bar under a tensile load stretches 0.00050 in. in a length of 2.00 in. Find the amount of strain in inches per inch; in per cent.

7. A portion of a steel bar 0.500 in. long was loaded in such a manner that the change in length was 0.00040 in. What was the strain?

8. State Hooke's law. Upon what basis of evidence was it first accepted? Is it rigorously true? Is it a useful guide for design?

9. A round steel bar is 0.750 in. in diameter and it supports initially a load of 3,600 lb., which is then increased to 12,000 lb. While the load is being increased, a portion of the bar 10 in. long stretched 0.0067 in. Compute the increase in strain, the increase in stress, and the modulus of elasticity.

10. A flat bar of cold-rolled phosphor bronze 0.902 in. wide and 0.210 in. thick supports an axial tensile load of 5,000 lb. Using the value of modulus of elasticity given in Table IX, find the amount that a portion of the bar 2.00 ft. in length stretches under the 5,000-lb. load.

11. A magnesium-alloy block was originally 3.500 in. high, 1.000 in. thick, and 1.200 in. wide. It supports a vertical axial load in compression of such an amount that the height of the block was reduced to 3.495 in. Using the value of modulus of elasticity given in Table IX, find the amount of load on the block.

12. How are the average properties of a material determined?

13. A round steel bar 0.660 in. in diameter was loaded to failure in axial tension. The maximum load was 22,500 lb. Compute the tensile strength (ultimate) of the steel.

14. Explain how high stress concentrations due to notches on the surface of a machine part in axial tension under a steady load are relieved when the part is made of a ductile material.

15. It has been stated that if materials had no ductility, it probably would be impossible to design machine and structural parts by the use of the common formulas of mechanics of materials. Is this statement accurate? Give reasons for your answer.

16. Why should there be any distinction between the strength of a material of which a structural or machine part is to be made and the strength of the part itself?

17. A concrete cylinder 4.00 in. in diameter, when tested in compression, failed at a load of 72,000 lb. The failure occurred along a plane of approximately 45 deg. with the horizontal. Compute (a) the maximum compressive stress and (b) the shearing stress on the 45-deg. plane. What conclusion can be drawn regarding the relative strength of this concrete in shear and in compression?

18. A flat bar of steel 1.505 by 0.496 in. in cross section is loaded to failure in tension, the maximum load being 45,600 lb. The fracture is along an inclined plane at an angle of approximately 45 deg. with the action line of the load. Compute the maximum shearing stress in pounds per square inch.

19. A railroad rail is 30.08 ft. long at a temperature of 70°F. Assuming that no forces are applied to restrain the change in length of the rail, how much would the rail shorten if the temperature dropped to −15°F? How much would it lengthen if the temperature rose to 110°F? Will such changes in length actually take place under normal conditions of service in a track? Give reasons for your answer.

CHAPTER III

THE ELASTIC STRENGTH OF MATERIALS

Types of Failure of Materials. Four types of structural failure due to purely physical causes can be distinguished in machine and structural parts: (1) failure of elastic properties, marked by permanent distortion, sometimes leading to collapse; (2) failure by flow, as of a viscous liquid, usually under elevated temperatures but sometimes at ordinary temperatures, as in the case of very soft metals like lead; (3) failure by actual fracture, either under a steady load or by a gradually developing fracture under repeated loading; and (4) failure by the gradual wearing away of materials under abrasive load. In addition to these physical causes of failure, chemical action, acting either alone or in connection with loading, sometimes causes failure by corrosion, and organic materials, such as wood, are sometimes destroyed or injured by the action of bacteria or the devouring action of insects or worms. Failure may also be caused by the action of heat, either the chemical action of combustion, the softening action of heat when applied to metals and plastics, or the removal by heat of the water of crystallization necessary to the solidity of cemented materials. In this chapter the first type, elastic failure, will be considered.

Elastic Action in Ideal and in Actual Materials. By definition a perfectly elastic body, after the application and removal of load, returns to its original size and shape. This does not necessarily mean that Hooke's law of the proportionality of stress to strain holds. A diagram for an elastic material plotted with values of stress as ordinates and values of strain as abscissas (called a *stress-strain* diagram)[1] might be a curved line as shown in Fig. 7*b* so long as the body returned to its original shape after the removal of load. It would not be necessarily true that the *energy* stored up by a series of increasing loads was entirely given out as

[1] In Fig. 7 the common practice is followed of computing stress on the basis of the original cross section of the specimen, and of computing the elongation (or shortening) of a gage line of given length along the specimen. Actually the area of the cross section diminishes under tension and increases under compression. The strain is not uniform along the gage line, especially as fracture becomes imminent. The result of a test in which stress is computed on the basis of actual minimum cross section under any given load and in which the strain is computed by taking into account the change of strain under varying cross-sectional area is called a *true* stress-*true* strain diagram (see reference 10 at the end of this chapter).

mechanical energy when the load was removed. A stress-strain diagram such as that shown in Fig. 7c would be that of an elastic body in which some of the energy of strain was lost, presumably as heat, during a cycle of loading and unloading. The energy lost would be measured

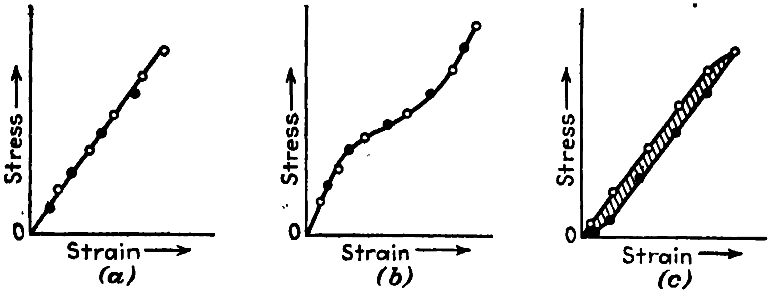

FIG. 7. Stress-strain diagrams for elastic material.

by the area of the shaded part of Fig. 7c, and such lost energy is known as *mechanical hysteresis*.

Actual materials are, probably, never perfectly elastic under any loading, although many rolled metals are so nearly elastic that, within a certain limiting stress, the permanent set after removal of load can be detected only by measurements of extraordinary delicacy. Stress-strain diagrams for actual materials under increasing and decreasing loads are very rarely, if ever, found to take the form of Fig. 7b. For a range of stress within which a material may be considered as elastic, the stress-strain diagram may be considered to have the form shown in Fig. 7a. Figure 8 shows the typical form for the stress-strain diagram for a range of stress sp (or Op') extending into the region of inelastic action. The action under decreasing loads may, with a fair degree of accuracy, be represented by the line pr parallel to the straight line Om, and q may, with a fair degree of accuracy, be considered to be the amount of permanent set remaining after the removal of load.[1]

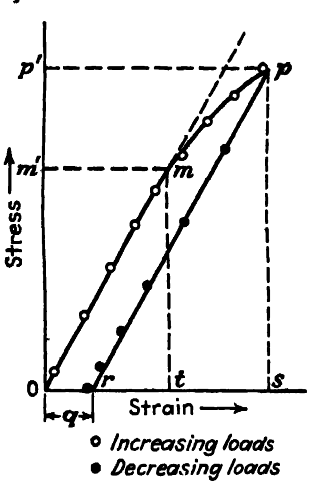

FIG. 8. Stress-strain diagram showing inelastic action.

[1] If q in Fig. 8 is very small, it does not measure the set very accurately. For example, in a piece of aluminum, if q were taken as 0.2 per cent strain, then it would

Structural Damage Caused by Inelastic Action in Materials. Before considering practical methods of determining the limiting stress for the elastic action of a material, it may be well to consider the damage done to a structural or machine member by inelastic action. Many such parts are obviously damaged by permanent distortion. An example of such damage is a permanent twist in the shaft of a gearshift in an automobile. This shaft carries one or more sliding gears driving the shaft through keys in a keyway, and if the shaft is permanently twisted the gears will not slide, and the shaft ceases to function properly. Another example is furnished by a beam from which a plaster ceiling is supported. If any serious permanent deflection of the beam takes place, the plaster ceiling will sag and probably crack.

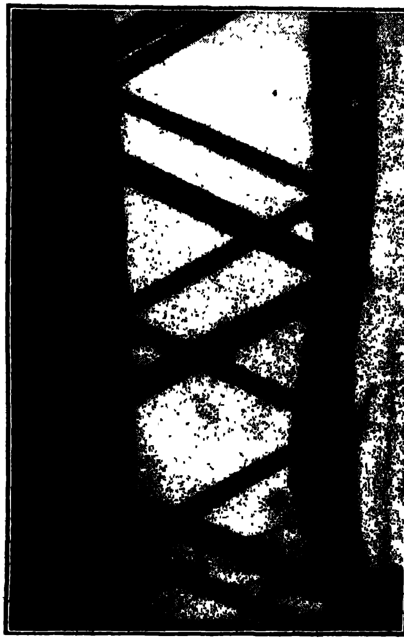

FIG. 9. Elastic failure of a steel column, resulting in collapse.

In the case of a post carrying a compressive load, the damage will be even more serious. Under compression, inelastic action in a post is frequently followed by buckling (sidewise deflection) followed by collapse as shown in Fig. 9. In fact, under compressive loading, the beginning of appreciable inelastic action may, for practical purposes, be regarded as the ultimate strength of the structural or machine part, if the part is likely to buckle under compression.

Inelastic action in a machine or structural member does not usually cause serious damage unless it extends over a considerable volume in the member. Localized inelastic action may occur at the edge of a small hole, at the root of a screw thread on a steel bolt, and *unless the member is subjected to repeated loading, or is exposed to low temperature*, no appreciable damage results. However, the screw thread on a bolt made of *cast iron*, or other brittle metal, *does* seriously reduce the tensile strength of the bolt.

represent quite closely a set of 0.2 per cent permanent set after the removal of the stress ps; if, however, q were taken as 0.01 per cent strain, then the permanent set after removal of the stress ps would probably differ by an appreciable percentage from 0.01 per cent.

In a brittle metal there is not sufficient ductility to allow relief of the high stress at the root of the screw thread to prevent fracture under a low tensile load.

No steel frame building is free from localized high stress at rivet holes and at edges of beam supports, especially during the process of erection. The development of spreading cracks at such points of localized overstress would indicate the progress of a failure by fracture after many cycles of repeated stress—a "fatigue" failure as it is rather inappropriately called.

Tests to Determine the Practical Limit of Elastic Strength, Yield Point, Yield Strength. To the designer or the user of machines and structures, a very important value to be determined in connection with elastic failure is *a limiting stress below which the permanent distortion of the material is so small that the structural damage is negligible, and above which it is not negligible.* It is evident that the amount of distortion which may be regarded as negligible varies widely for different materials, and for different structural or machine parts.

In connection with this limiting stress for elastic action a number of technical terms are in use; some of these terms and their definitions are

1. *Elastic Limit.* The greatest stress which a material is capable of withstanding without a permanent deformation remaining upon release of stress.

2. *Proportional Limit* (sometimes called proportional elastic limit). The greatest stress which a material is capable of withstanding without a deviation from the law of proportionality of stress to strain (Hooke's law).

3. *Yield Point.* The stress in a material at which there occurs a marked increase in strain without an increase in stress. (NOTE: under this definition only a few materials, mostly ductile steels, can be truly said to have a yield point.)

4. *Yield Strength.* The stress at which a material exhibits a specified limiting permanent set. This set is usually determined by the approximate method of regarding the percentage of deviation from Hooke's law at any given stress as equal to the percentage permanent set after removal of that stress. In Fig. 8, q is taken as a measure of set.

As defined above, the elastic limit and the proportional limit are idealized properties. Even with the most delicate instruments imaginable, all that could be determined would be an elastic limit at which no permanent set could be observed greater than the smallest strain the strain-measuring micrometer could detect, or a proportional limit at which no deviation from proportionality of stress to strain (stress-strain diagram a straight line) greater than the smallest strain measurable with the apparatus used. The smallest set detected or the earliest deviation from Hooke's law of proportionality of stress and strain would depend on sensitivity and accuracy of instruments, skill in handling, scales chosen for plotting stress-strain or stress-set diagrams, and the particular curved ruler used in drawing in a curved part of the diagram.

In the second place it is by no means certain that any actual material has an absolute elastic or proportional limit. At low stresses, slight localized inelastic actions can be detected if sensitive strain-measuring apparatus is used.

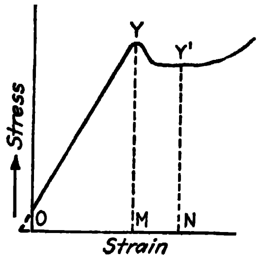

FIG. 10. Stress-strain diagram for a metal having a well-defined yield point. MY, "upper" yield point, is shown by "drop of beam" or by "halt of pointer" of testing machine. NY' is "lower" yield point.

In the third place it is doubtful whether slight inelastic action constitutes appreciable structural damage to the materials of most structures and machines.

If a material has a well-defined yield point, as defined above, that yield point does furnish a fairly satisfactory criterion of structural damage. Figure 10 shows a typical stress-strain diagram for a material with a yield point. At Y it is evident that there is increase of strain without increase of stress. The only materials which do have a yield point are the ductile grades of steel and iron, a few nonferrous metals, and possibly some plastics.

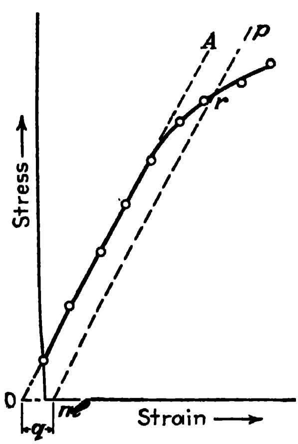

FIG. 11. Yield strength of material having no well-defined yield point; q is called the "offset."

Since most materials do not have a yield point, some other index of elastic strength is desirable. Perhaps the most satisfactory in use today is an arbitrary limit called the *yield strength.*[1] Its determination involves the selection of an amount of permanent set which serves as marking the limiting amount of permanent deformation which a material can have without appreciable structural damage. This arbitrary value will be different for different materials and for different uses for the same material. It may well be chosen by some standardizing body, such as a technical society.[2] There is also involved the taking of data of stress and strain and the drawing of a stress-strain diagram, such as that shown in Fig. 11.[3] Then the arbitrary value for set is laid off as q in Fig. 11 and the line mp drawn parallel to OA, the straight portion of the stress-strain

[1] See reference 5 at end of this chapter. Some confusion has been caused by the use of the two terms "yield strength" and "yield point." In England the term "proof stress" has been used in place of "yield point."

[2] For several metals a limiting set of 0.2 per cent has been found satisfactory for locating yield strength.

[3] In Part I of 1949 "Standards" of the A.S.T.M., p. 1241, there is described a

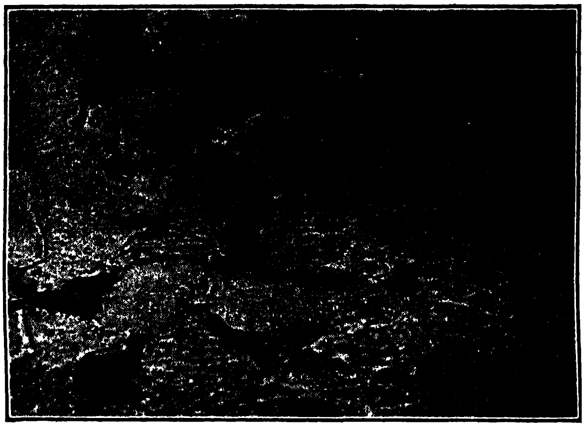

FIG. 12. Micrograph of structural steel stressed below yield point. Magnification 600 times. (*Micrograph by N. J. Alleman and N. H. Roy in the University of Illinois Metallographic Laboratories.*)

FIG. 13. Micrograph of structural steel stressed above yield point. Magnification 600 times. (*Micrograph by N. J. Alleman and N. H. Roy in the University of Illinois Metallographic Laboratories.*)

diagram. The intersection r of mp with the stress-strain diagram determines the stress at the yield strength.

While the yield strength is an arbitrary value, that fact does not destroy its usefulness.[1]

method of determining yield strength which is applicable to metals whose general properties are well known, and which does not require the drawing of a stress-strain diagram.

[1] In the rare case in which very slight permanent distortion constitutes distinct structural damage, as is the case for certain parts in mounts used in the army and in the navy for heavy guns, then the arbitrary value of limiting stress would be much

The Mechanism of Inelastic Action (Slip). Considerable light is thrown on the mechanism of elastic failure of materials by examination under the metallurgical microscope of surfaces of materials stressed beyond their elastic strength. Figures 12 and 13 are photomicrographs of a specimen of steel before and after straining beyond its elastic strength. In Fig. 13, across the faces of a number of the crystalline grains of the metal can be seen fine lines which are known as *slip lines* or *slip bands.* These lines or bands mark places where sliding has occurred between thin plates (laminae) of metal within a crystalline grain. Figure 14 is a

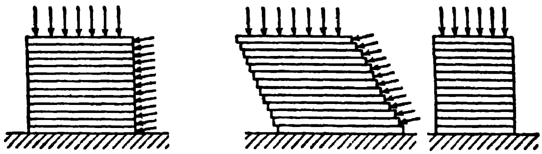

FIG. 14. Diagram illustrating the action of slip.

diagram illustrating, or rather cartooning, this sliding action, which, in a rough way, resembles the sliding action of a pile of boards. Many experimenters have shown that this sliding takes place along certain definite planes in the pattern (space lattice) formed by the regular geometrical arrangement of atoms in a crystalline grain, and along the slip plane most nearly in the direction of the maximum nominal shearing stress.

Microscopic examination of slip in nonmetallic materials is a field of investigation as yet so very little studied that little is known about the mechanism of elastic failure of wood, concrete, brick, hemp, leather, rubber, and plastics.

Slip does not occur to any appreciable extent in any of the ordinary materials of construction until a fairly well-defined limiting stress has been applied, and if slip occurs it does not continue indefinitely, under load, but ceases after a short time. In this respect slip differs from the slow flow under load of a viscous (thick, sticky) liquid such as pitch, sealing wax, or steel at temperatures approaching fusion. In such a

less than 0.2 per cent, perhaps about 0.01 per cent. For such a small limiting set the difference between actual set after a stress and set as determined by deviation from Hooke's law (deviation from a straight stress-strain line) would be appreciable and the limiting stress can best be determined by applying a series of increasing stresses, releasing the load after the application of each stress, taking a delicate measurement of set remaining after each stress, drawing a stress-set diagram, and locating the yield strength at the junction of the stress-set diagram and the line representing the arbitrary small limiting set.

liquid any force will produce flow, and will cause the flow to continue as long as the force is applied, the rate of flow depending on the magnitude of the force applied. *Plastic* is the term used to characterize the inelastic slip, and plastic action is to be distinguished from viscous flow. The viscous flow of materials of construction, especially under elevated temperatures, is discussed in the next chapter.

Behavior of Materials in a Partially Plastic State. In most cases the material of structures and machines is subjected to stresses so low that the action is almost perfectly elastic. The behavior of material under stresses so high that plastic action is set up is of interest for three reasons: (1) In the process of shaping and fabricating the material it is not infrequently necessary to bend, to stretch, or to punch the material cold; (2) the behavior of the material under accidental overloads is frequently of importance, and for some members, such as ball and roller bearings, the stresses at points of contact are above the elastic range; (3) ductility under loads above the elastic strength is a good insurance factor against disastrous, shattering collapse or fracture under an occasional overload.

In fabricating members of steel structures, such as beams and columns, it is frequently necessary to bend them to shape or to punch holes in them. These processes involve local stresses beyond the yield point of the material. A material which possesses high ductility is not seriously injured by such treatment, but brittle material under such conditions would be shattered.

In selecting the material to be used for a structure or a machine, it is frequently of importance to consider the effects of accidental overload. An excellent example is furnished in the selection of material for parts of railway rolling stock, such as car couplers, draft rigging, side frames, etc. For such parts it is evident that a tough material which, even after it is badly distorted, still possesses considerable strength is preferable to a brittle material which, though it may stand a higher stress before rupture, snaps suddenly with very little strain or other warning of approaching failure, if rupture does occur. A material which after severe distortion still possesses high strength is called *tough*. Figure 15 gives stress-strain diagrams for a tough material and for two others less tough.

The desirability of insuring the parts of railway cars against sudden, shattering failure has caused the very general replacement of cast-iron parts by steel castings. For a similar reason cast-iron columns for buildings have been generally discarded in the best practice. It is a general rule in machine design not to use a brittle material in direct tension.

In parts of machines which involve the carrying of heavy loads on spherical or cylindrical surfaces—such as ball bearings, roller bearings,

car and wagon wheels, chain links—there are set up, in service, localized stresses beyond the elastic strength of the material. Such parts do not last indefinitely; they wear out, and their length of life is dependent on the properties of the material when stressed beyond the elastic strength. In wire rope, band saws, and other flexible machine parts that, in use, are repeatedly bent as they pass round pulleys and sheaves, the yield point of the material is frequently exceeded, and such members show considerable permanent distortion after a short time in service, and finally wear out.

Effect of Stress beyond the Yield Point. In 1881, Johann Bauschinger of Munich published the results of a long series of experiments which demonstrated that, if a ductile material is stressed in one direction beyond its yield point, for subsequent stress in the same direction, the elastic strength is raised, that for subsequent stress in the reverse direction the elastic strength is lowered, and that in any case the toughness of the material is diminished. Figure 16 illustrates the properties of material stressed beyond the yield point. Bauschinger also showed that time is necessary for the particles of the material to adjust themselves after overstress, and that for subsequent stresses in either direction the elastic strength of overstressed materials is raised by rest.

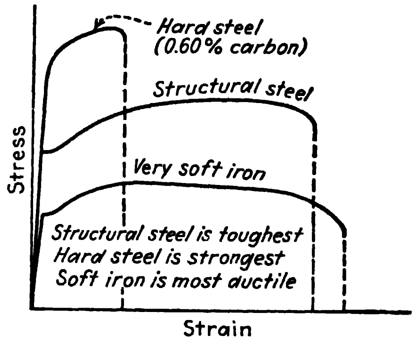

FIG. 15. Stress-strain diagrams showing different degrees of toughness. The area under each stress-strain diagram is a measure of the toughness of the metal.

The properties of cold-rolled steel and of cold-drawn wire are explained by Bauschinger's tests, as is the "springiness" of hammered (peened) steel or brass plates. In the process of cold-drawing or cold-rolling the material is stretched well beyond its elastic strength. Steel, iron, copper, brass, aluminum, and zinc have their elastic strength raised by cold-rolling, cold-drawing, cold-hammering, or shot peening. The cold-working of metal generally decreases its ductility and its toughness. To a large degree heating followed by slow cooling (annealing) removes the effects—beneficial and injurious alike—of cold-working. The resistance of most metals to repeated stress is increased by cold-working, but the percentage of increase is not so high as for elastic strength.

The "Aging" of Metals. After cooling to ordinary atmospheric temperature there takes place in most of, if not in all, the common metallic materials of construction a slow change known as "aging." Probably this aging is due to the gradual establishment of equilibrium for molecules or space-lattice units which do not reach equilibrium during

cooling. Aging, then, is a process which closely resembles "precipitation hardening" of metal. Aging of metal increases its yield strength, its tensile strength, and its strength under repeated stress. The greatest gain is usually in yield strength.

Aging of metal at room temperature is called "natural" aging, and several days are required before the metal reaches its maximum strength. "Artificial" aging at temperatures of a few hundred degrees Fahrenheit will increase the yield strength to its maximum in a few hours, but in some metals the resistance to fracture under repeated stress is very slightly increased by "artificial" aging. This suggests the idea that the

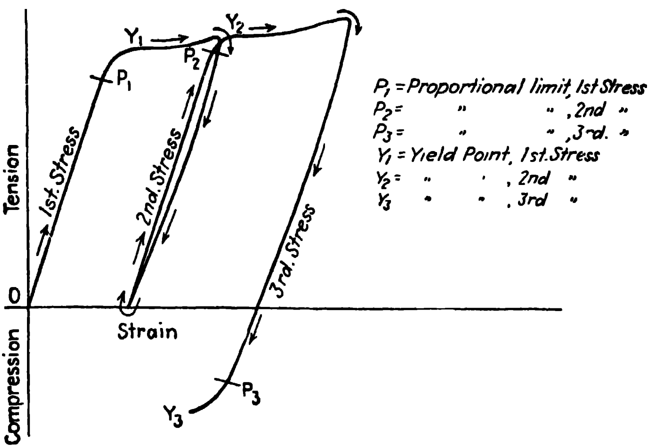

FIG. 16. Stress-strain diagram showing the effect of a few rep ons of stress beyond the yield strength.

increased strength given by aging a metal is gradually reduced under repeated loading or perhaps by long time under a steady load. Under natural (room-temperature) aging the decay of strength occurs very slowly indeed, and may in many cases be neglected, but under "artificial" aging the gain of strength is rapid, and the loss of the gain of strength is also rapid.

The phenomenon of aging was first noted in nonferrous metals, and later was found to occur in ferrous metals. It is a factor of importance in determining the strength and ductility of metals after considerable time has elapsed following their fabrication into structural or machine parts. Aging metal usually distorts it less than does cold-working.

The Slip-interference Theory. Under a load a little beyond the elastic strength, *slip* of the metal soon ceases and the elastic strength to resist a second load is increased. This is explained by the *slip-interference theory* of Jeffries and Archer (see reference 1 at the end of this chapter). As slip takes place, crystalline grains of metal are "frag-

mented" into smaller cohering bodies called crystallites, and the boundaries of these crystallites act somewhat like the grain boundaries of the larger crystalline grains in that they hinder and sometimes stop the further spread of slip and of the resulting cracks which sometimes start from slip bands.[1]

In addition to this action of the crystallites, adjacent crystalline grains nearly always have the atomic planes, on which alone slip can take place, lying in different directions and, as slip proceeds, the slip in one crystalline grain is hindered as it attempts to enter another grain. Moreover, in metals composed of two or more kinds of crystalline grains (medium-carbon steel, for example), the stronger grains act as "keys" tending to stop, or at least to hinder, the progress of slip in weaker grains.

The slip-interference theory further holds that in a metal there may be expected to be a definite small-size grain which will be more effective as a "brake" on slip than larger, more widely scattered grains, and also more effective than extremely small grains, which are so small that slip can proceed right by them without much deviation from its direct path. In the case of steel, such an "optimum" (best, more effective) size of grain may be produced by heat-treatment.

Theories of Failure of Materials. Which action, stress or strain, causes structural *damage* in the material of a structural or machine part? Or is structural damage caused by *energy*, which involves both stress and strain? The answer to these questions is still a matter of vigorous debate, and there are five theories for the cause of failure, namely the *maximum-stress theory*, the *maximum-strain theory*, the *maximum-shear-stress (or strain) theory*, the *maximum-total-strain-energy theory*, and the *maximum-shear-strain-energy theory*. This last-named theory is more correctly called the *maximum-distortion-energy theory*. For a discussion of these different theories, see reference 3 at the end of this chapter.

The theory of strength of materials usually given in elementary textbooks on mechanics of materials is the maximum-stress theory, and in such books little account is taken of the effect of lateral strain, or the "Poisson's ratio effect" as it is sometimes called; this is equivalent to assuming a value of zero for Poisson's ratio. For most cases met in practice the common theory gives results of sufficient accuracy, except as noted below.[2]

[1] The use of the term "fragmented" may be somewhat confusing. The crystallites are not separate fragments, but are assumed to be small bodies cohering to make up what was a single crystalline grain.

[2] For homogeneous material subjected to stress of opposite sign (*e.g.*, tension and compression) in two directions at right angles, as, for example, a hollow tube under heavy axial compression and internal hydraulic pressure, the *maximum-stress theory* yields results distinctly on the danger side of those given by the other four theories, and tests for yield strength agree with this.

In the case of *elastic failure* the evidence of the microscope makes the maximum-shear theory seem reasonable, since slip seems to be very much like a shearing action. Moreover, the maximum-shear theory yields results which, in general, are on the *safe side* of those given by the other theories. The maximum-shear-strain-energy theory seems to fit observed test results for elastic strength as well as, and perhaps a little better than, the maximum-shear-stress theory.

Resistance of Materials to Impact. In selecting materials for members which must resist impact, it must be borne in mind that there are two factors to be considered: total *stress* allowable in the member and total *strain* allowable. Resistance to impact is a function of *both* these factors. In this connection it may be noted that "the force of a blow" cannot be computed unless not only the *energy* of the blow is known but also the rigidity of the body striking the blow and of the parts on which the blow is delivered; for example, a piece of iron weighing 100 lb. falling from a height of 20 ft. would deliver 2,000 ft.-lb. of energy when it struck a body, but the *force* set up if it struck soft earth would be much less than the force set up if it struck a rigid concrete foundation.

For materials which must withstand heavy accidental impact without actual rupture, *toughness* is the prime requisite. Toughness has been defined on page 26 and it may be noted here that the toughness of a material may be measured by the *area under the stress-strain diagram* for that material (see Fig. 15). A striking illustration of the resistance of materials to rupture under impact is furnished by comparing the action of oak with that of cast iron. Under static load cast iron is about three times as strong as oak, but the *strain* which oak will stand before it is ruptured is about nine times the strain which cast iron will stand. The area under the stress-strain diagram for oak is about three times that for cast iron, and under impact loads oak requires about three times as much energy for fracture as cast iron.

The ability of a material to resist impact without permanent distortion is measured by the area under the stress-strain diagram up to the elastic limit (for practical purposes up to the yield strength). If elastic resistance to impact is desired, a material with a high elastic strength or a low modulus of elasticity should be used. A good illustration of the difference between elastic resistance to impact and resistance to rupture under impact is furnished by a comparison of the action of high-carbon steel with that of low-carbon steel. High-carbon steel has the higher yield strength and has a greater area under its stress-strain diagram up to the yield strength. It is superior to low-carbon steel in its *elastic* resistance to impact and is used for such members as springs. Low-carbon steel, however, has a greater area under the *whole* of its stress-strain diagram than has high-carbon steel (see Fig. 15) on account of its much greater

ductility and low-carbon steel offers greater resistance to *fracture* under impact than does high-carbon steel, and is used for such members as chains and car couplers in which ability to withstand occasional heavy shock without rupture is of great importance. Wrought iron has a low elastic resistance to impact, but like low-carbon steel has a high resistance

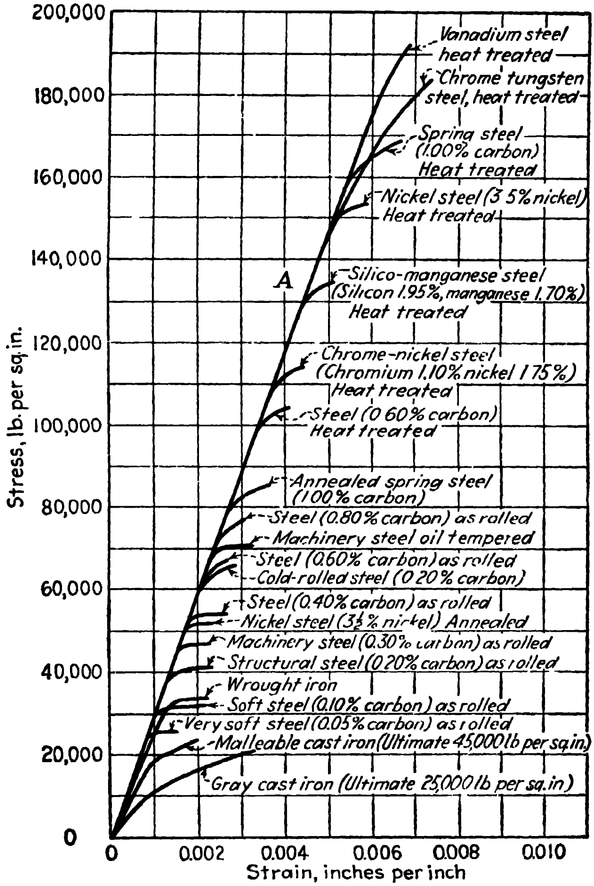

FIG. 17. Stress-strain diagrams for various grades of iron and steel.

to rupture under impact. In this respect it does not show any marked superiority to the better grades of low-carbon steel, but is superior to the poorer grades.

In considering resistance to static load, it is, in general, necessary to consider only the stresses set up in the most-stressed fibers of a member—in the smallest cross section of a rod in tension, for example. If a machine or a structure is to withstand impact, the *total deformation* of any

part is effective in increasing the resistance to impact. Two rods of the same material with equal cross section have the same static strength in tension irrespective of their relative lengths; but their ability to withstand energy of impact varies directly as their length.

Stiffness, Significance of the Modulus of Elasticity. The modulus of elasticity of a material is an index of its elastic stiffness or rigidity and is the ratio of stress within the proportional limit to the corresponding strain. The stiffness or rigidity of a strong material under working loads may be no higher than the rigidity of a weaker material. The best illustration of the distinction between strength and stiffness is found in the action of steel. All grades of steel from the softest rivet steel to the hardest tool steel have about the same modulus of elasticity—30,000,000 lb. per sq. in. This is illustrated in Fig. 17, which shows typical stress-strain diagrams for various grades of steel. In Fig. 17 the slope of the line *OA* closely indicates the value of the modulus of elasticity for all the steel specimens. If the stresses actually set up in a machine member or structural part are within the limit of proportionality, it makes no difference in the rigidity whether soft steel or hard steel is used. In machine tools it has sometimes been proposed to remedy too great deflection by replacing the flexible parts with others made of a stronger, harder steel; this usually does no good, as the stresses in machine-tool parts are usually low, and it is the modulus of elasticity of the steel rather than the strength which counts. The use of high-strength nickel steel for long-span bridges will allow the use of smaller structural members, but the stiffness of the bridge will be somewhat diminished by the use of these smaller members.

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Questions

1. Name and characterize four types of physical failure of materials.

2. What is mechanical hysteresis? Give examples of structural damage caused by mechanical hysteresis; of parts in which some mechanical hysteresis is desirable.

3. What damage is caused to materials of construction by inelastic action? Give illustrations.

4. Tell the difference between the effect of inelastic action under a single load over a very minute area, and the effect caused by millions of repetitions of the same load which caused the inelastic action.

5. Define the technical terms, elastic limit, proportional limit, yield point, yield strength. Do all materials have a yield point? Give examples.

6. What is slip, and what are slip lines? Describe the action of slip in a material.

7. Distinguish between plastic action and viscous flow.

8. Define toughness, and name several tough materials.

9. What is the effect on the subsequent elastic strength of a material of exceeding the original elastic strength, (1) the subsequent loads being in the same direction as the first load, (2) the subsequent loads being in the opposite direction to the first load?

10. Define cold-working of a metal. Discuss the effects of cold-working on the elastic strength, the tensile strength, and the ductility of a metal.

11. Briefly outline the slip-interference theory.

12. State five theories of elastic failure.

13. Explain why oak is weaker than cast iron under steady load, but can withstand more energy of impact without fracture than can cast iron

14. Would elastic failure of a tie rod be as disastrous as elastic failure of a long column? Explain.

15. If you were asked to state the yield point of cast iron, what would you reply?

16. It has been stated that if materials had no ductility it would be impossible to design structural and machine parts by the use of the common formulas of mechanics of materials. Is this statement accurate? Give reasons for your answer.

17. A tension specimen 0.505 in. in diameter is placed in a testing machine and load applied with the following results. The specimen did not fracture.

Load, lb.	Stretch in 2 inches, in.
975	0.0002
2,200	0.0007
3,400	0.0011
5,000	0.0018
6,200	0.0022
8,000	0.0029
9,100	0.0036
9,300	0.0054
9.325	0.0079

Determine the yield strength for an "offset" of 0.02 per cent; for an "offset" of 0.05 per cent.

CHAPTER IV

THE FAILURE OF MATERIALS BY FLOW OR CREEP

The Phenomena of "Creep" of Materials. If solids are heated to a sufficiently high temperature, and if chemical decomposition does not take place, they are melted. In most cases, at temperatures well below those required for complete fusion, evidence is given of the beginning of the liquefying process, and the material begins to act somewhat like a very viscous liquid. This action is illustrated by the softening of an asphalt pavement on a hot summer day, and by the sagging of steel beams caused by the heat of a conflagration.

The most marked effect of this elevated temperature is to cause a very slow flow or "creep" to take place under stress. The rate of flow of a given metal depends on the magnitude of the stress and on the temperature. Whether for any given temperature there is a definite limiting stress below which flow absolutely ceases is an unsettled question, as is also the question whether there is a definite limiting *temperature* below which flow absolutely ceases. For practical purposes of design and use of materials, limiting stresses and temperatures may be determined below which the rate of flow is so small as to do no appreciable structural damage during the expected "life" of a machine or structural part.

Creep Compared with Slip. In a solid metal in which creep is taking place, inelastic action (slip) may be present also. Structural damage by distortion is a common feature for both creep and slip. The limiting stress for negligible *slip* of a metal is better defined than the limiting stress for negligible *creep*.

For steel and most of the common materials of construction at ordinary temperatures, when slip has occurred under a given stress, the motion of distortion diminishes after a short time; below the ultimate strength, slipping intracrystalline flakes soon come to rest, even though the stress which started the slip is still acting. Creep, on the other hand, continues as long as the stress is applied, or until the material is actually fractured. Figure 18 is the graph of a test of lead showing creep to fracture at 150°F. The slope of the graph is a measure of the *rate* of flow, and it will be noted how the rate of flow decreases from the beginning of the test to about 1.0 per cent total creep (A), remains practically constant during the middle portion of the test (AB), and increases during the last stage of the test (BC).

Damage Due to Creep. Creep in a material causes distortion, and in that respect resembles inelastic failure by slip, but the tendency of creep to continue *indefinitely* under load brings in the danger of *progressive structural damage by long-time steady loading.* Creep continued long enough produces fracture.

Materials Subject to Creep. Metals at elevated temperatures furnish the most conspicuous examples of failure by creep. At ordinary atmospheric temperatures, none of the common stress-carrying metals shows dangerous creep. In fact, the limiting condition for the development

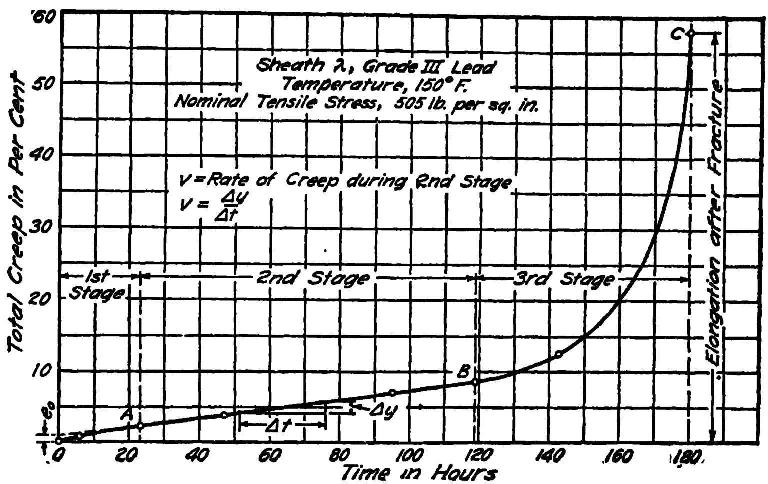

FIG. 18. Graph of a creep test of lead.

of efficient heat engines is the lack of known metals which, without disastrous creep, can withstand the required combination of high stress and high temperature. Some soft metals, such as lead and zinc, show distinct creep at ordinary room temperatures, and under the extreme stress developed near the ultimate in an ordinary tension test, most metals show a distinct "necking down" which seems to indicate appreciable flow of the metal.

Organic materials, notably wood, suffer chemical decomposition before developing any very large amount of creep. However, wood fractures under a long-continued stress about half as great as that which will cause fracture in an ordinary testing machine test. Some plastics show distinct creep at room temperature. Burnt-clay products include the materials most resistant to creep at high temperatures, but even burnt-clay products show signs of flow at very high temperatures. Under long-continued steady load, concrete shows appreciable creep.

Determination of Practical Creep Limit. Before the importance of the *time element* in creep came to be realized, it was customary to evaluate the strength of a material under high temperatures by ordinary short-time tension tests. There have been some experimenters who hold that the very precise determination of proportional limit (see page 20) at any given temperature locates the practical limiting stress for creep at that temperature. The reliability of the short-time proportional-limit test for creep is today considered decidedly doubtful.

To carry out tests covering the actual length of service required for machines and structural parts would require years of experimentation for each material tested. This would be impracticable. Some test for creep limit, a test which can be carried out within a reasonable time and which will yield a reliable criterion of strength for metals under long-time service, is much needed.

Total Creep and Rate of Creep. P. G. McVetty of the Westinghouse Research Laboratories uses the rate of creep under different temperatures, times, and stresses as a measure of the strength and expansion of the metal. He determines the total creep for any metal by a series of tests of specimens, in which the stress, the temperature, and the creep during various intervals of time are measured. Such a creep diagram is shown in Fig. 18. The rate of creep is measured by the slope of the creep-time diagram at any point. There is a short first stage, in which the *rate* of creep is fairly high (OA in Fig. 18); then a second stage (AB), a long time during which the creep rate is fairly constant; and a third stage (BC), in which the rate of creep shows a great increase, and finally fracture occurs. The beginning of this third stage marks the beginning of fracture, and may be used safely as a measure of time to fracture under the given temperature and stress. The method of measuring the creep rate is shown in Fig. 18.

Figure 19(a) shows this method as applied to the test of a specimen of commercial lead tested at constant temperatures and for stresses at 200, 300, and 400 lb. per sq. in. for 1,600 hr. However, in this length of time none of the specimens fractured or reached the "third stage" of creep. Figure 19(b) shows the rate of creep in the second stage for the range of stress (200 to 400 lb. per sq. in.). By extrapolation, assuming the rate of strain to stay constant, the creep which may be expected after one year is shown, but the length of time to fracture or to the beginning of the third stage of creep is not shown, and may have been less than one year.

Creep Limits for Various Metals. The basis for a creep limit which shall be a reliable index of safety against structural damage by undue distortion under long-continued load is an arbitrary choice of a value suited to the particular metal under consideration and the service which

the structural or machine part has to withstand. A creep of 0.1 per cent per year has been suggested for steel for piping and bolts. A value of ¼ per cent per year has been suggested for lead sheathing for cables. Creep limits based on 0.1 per cent creep per year are given for several steels and for one nonferrous metal in Figs. 41 and 42 in Chap. VI.

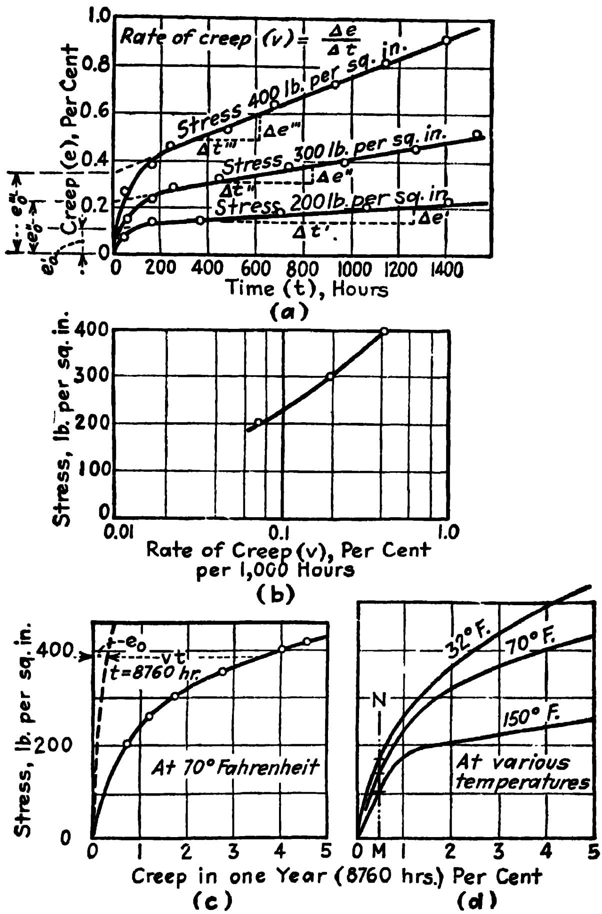

FIG. 19. McVetty diagrams for determining creep.

Mechanism of Creep in Metals. Figure 20 shows micrographs of the same area on a tensile specimen of lead after successive intervals of time under a steady load. Figure 20*a* shows the unstressed metal. The straight lines are scratches from the microtome knife used in shaping the specimen, which was unetched throughout the test. Figure 20*b* shows the appearance of the area after 48 hr. under steady load. It will be seen that some "slip lines" have appeared within grains and that grain

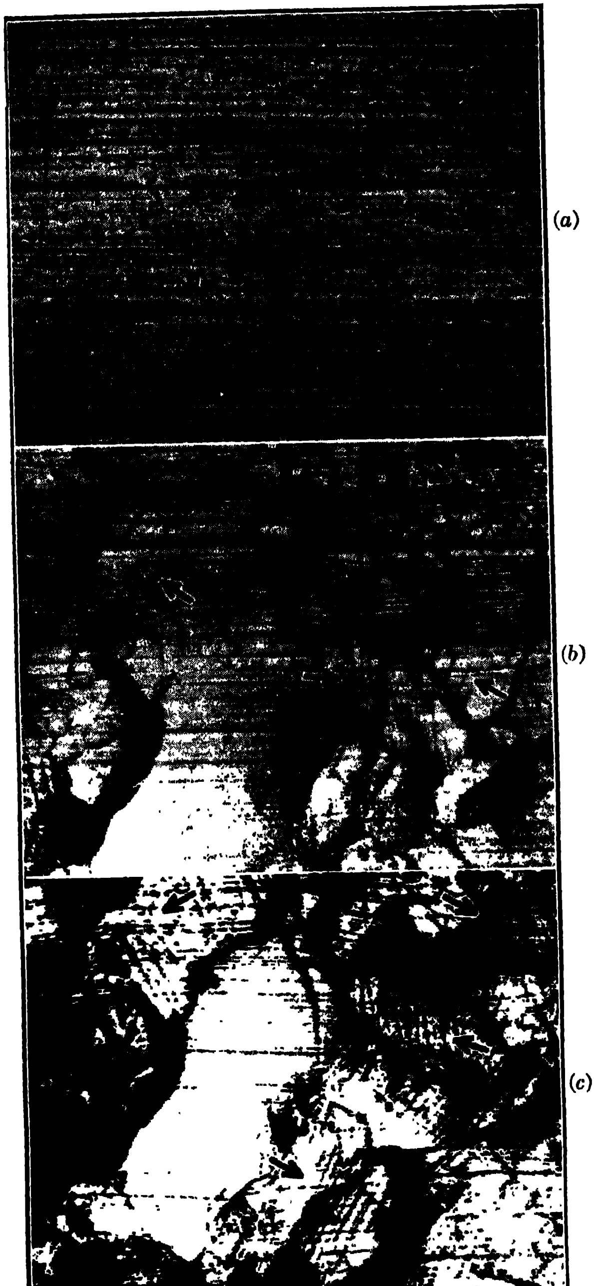

FIG. 20. Micrographs showing rotations of grains and development of slip bands in grains during creep in a specimen from lead cable sheathing: (a) unstressed; (b) after

boundaries have appeared, although no etchant has been used. The appearance of grain boundaries indicates some rotation of grains in a plane perpendicular to the page, and rotation is also shown by offsets and bending of the microtome scratches at regions indicated by arrows. Figure 20c, taken after 96 hr. of creep, shows rotation of grains continuing and more slip lines appearing. It seems that in this specimen both intracrystalline slip and rotation of grains took place.

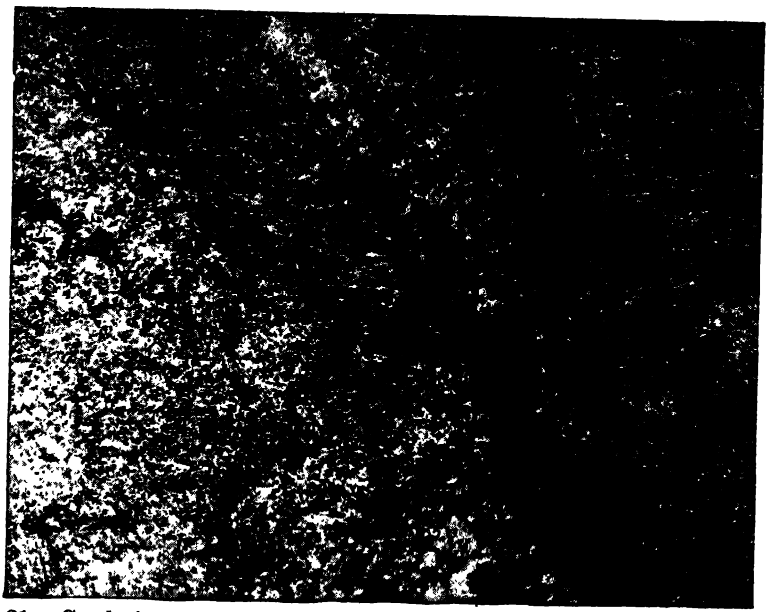

FIG. 21. Cracks in a tin-lead alloy after creep. Specimen was subjected to a steady tensile stress of 1,000 lb. per sq. in. for 525 hr. Magnification 400 times. (*Micrograph by B. B. Betty in Materials Testing Laboratory, University of Illinois.*)

Fracture under Creep. Fracture of metals under creep occurs as a spreading crack. Such a crack is shown in Fig. 21 in a specimen of a tin-lead alloy. Similar cracks have been observed by Tapsell in nickel-copper, nickel-chromium, and nickel-chromium steel (reference 1 at end of chapter). Hanson has observed such cracks in aluminum. The crack under creep spreads more slowly than a "fatigue" crack under repeated stress. In electric cable sheathing, cracks have been detected by leakage of insulating oil before they had spread far enough to cause

48 hr. under a tensile stress of 800 lb. per sq. in.; (*c*) after 96 hr. under a tensile stress of 800 lb. per sq. in. Magnification 135 times. All micrographs taken at same location on specimen. (*Micrographs by C. W. Dollins, Talbot Laboratory, University of Illinois.*)

a disastrous breakdown of the cable insulation by letting in moisture. Frequently under long-time load the elongation before fracture is less than is the case in an ordinary testing-machine test of the metal. A spreading crack would naturally cause a loss of elongation before fracture, just as would a notch in the metal.

The ideal way to determine fracture stresses and allowable working stresses for metals under creep for various lengths of time would be to make tests of specimens, some of them under stresses which are so low that they do not cause fracture after a time under stress as long as the desired "service life" of a machine part. However, some machine parts are required to have a service life of as much as 100,000 hr. (11.4 years), and tests carried on to so long a time before the machine part could be

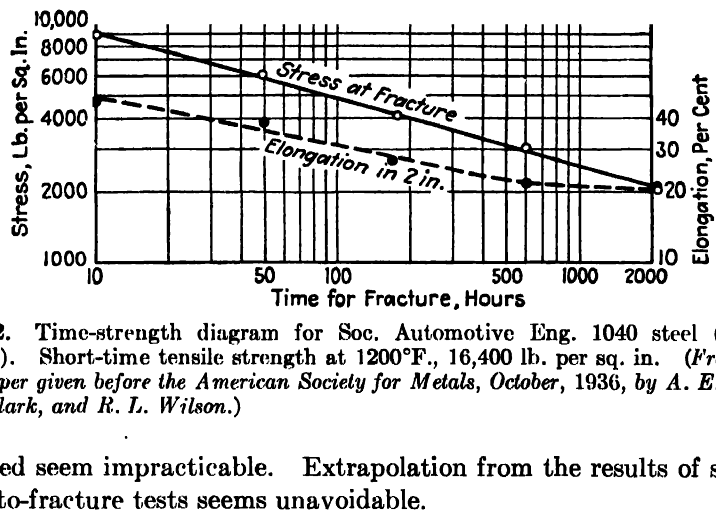

FIG. 22. Time-strength diagram for Soc. Automotive Eng. 1040 steel (electric furnace). Short-time tensile strength at 1200°F., 16,400 lb. per sq. in. (*From data in a paper given before the American Society for Metals, October, 1936, by A. E. White, C. L. Clark, and R. L. Wilson.*)

designed seem impracticable. Extrapolation from the results of shorter creep-to-fracture tests seems unavoidable.

Figure 22 shows the falling off of tensile strength (and of ductility) of specimens of mild steel at 1200°F. as length of time under stress increased. The maximum time under load in these tests was 2,000 hr. (83.3 days), and Fig. 22, plotted to logarithmic coordinates, shows a straight-line relation between tensile stress and time to fracture. However, other tests, some of them up to 10,000 hr., do not show a straight line in a log-log diagram, but the tensile strength falls below the values given by the straight-line diagram after 1,000 or 2,000 hr. See reference 11 at the end of this chapter.

At the present time, while it seems necessary to extrapolate results from test results up to 10,000-hr. tests, or in some cases from even shorter tests, it is highly desirable in determining allowable working stresses by such extrapolation to use very large "factors of safety" (See Chap. VII).

Although the weakening effect of holes, notches, and other stress raisers seems small in creep tests under high temperatures for a short time, it is very likely that they do weaken the metal under high temperature in long-time tests. The effect of stress raisers is discussed in the next chapter.

Structural damage to machine parts by creep may be caused by the expansion of rotating discs in a steam turbine at a temperature of, say, 800°F. or over, causing the discs or the blades to expand until there is rubbing against the casing, unless proper clearance has been allowed.

Creep under Repeated Stress at High Temperatures. In fatigue tests at temperatures high enough to cause creep, the effects of both creep and repeated stress must be considered. Under a steady load a creep test can be conducted with no "fatigue" effects, but under repeated stress at high temperatures both fatigue and creep come into the picture. As creep is a function of *time*, while fatigue damage is a function of number of cycles of stress, it is evident that the frequency of cycles of stress may be expected to affect the results of the tests. This has been found to be true, and the matter is further discussed in Chap. V.

Creep at Room Temperature. For iron and steel, and for most of the structural metals, creep, at stresses within the elastic range, does not become an appreciable factor in strength until a temperature of several hundred degrees Fahrenheit has been reached.[1] Lead, tin, and zinc show evidences of creep at ordinary room temperatures, as do such nonmetallic solids as asphalt, tar, sealing wax, glass, and some plastics.

Wood shows a distinct reduction of ultimate strength under long-time tests. The resistance both to shearing and to tensile stresses is much less along the grain of wood than across the grain. Possibly creep occurs in wood mainly along the grain.

R. E. Davis and H. E. Davis at the University of California and F. E. Richart at the University of Illinois have reported creep tests of concrete in compression and, at ordinary room temperatures, have obtained creep-time diagrams similar in shape to those shown in Fig. 18a. The chief danger of structural damage due to creep of concrete is not direct damage from the distortion of the concrete but from the transfer of stress from the creeping concrete to any steel reinforcing rods placed in it.

Creep of Nonmetals at High Temperatures. For the nonmetals the importance of creep depends largely on whether chemical change is caused at temperatures lower than those at which disastrous creep is liable to take place. Of course, if disastrous chemical action takes

[1] However, iron and steel do show signs of creep as the tensile (ultimate) stress is approached and the specimen begins to "neck down."

place before the temperature has risen high enough to cause damaging creep, the question of creep becomes of no further importance.

The ceramic materials, brick, terra cotta, tile, etc., withstand very high temperatures without disintegration due to chemical action, and they also have high creep strength. Their use as materials for machine parts subjected to very high temperatures, such as gas-turbine blades, is a matter for study and experiment. However, such ceramic materials in general have very little ductility. The use of high-temperature-resistant metals coated with a ceramic shell of still greater resistance to high temperatures is also under study and experiment.

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Questions

1. State the resemblances and the differences between creep and slip.

2. Under what conditions of temperature and time of loading is there danger of structural damage to materials due to creep?

3. Is creep an important cause of structural damage in bolts in rail joints? In bolts in high-pressure steam-pipe flanges? In lead sheathing for electric power cables? In a plain concrete wall? In a reinforced-concrete column? Explain in each case.

4. Compare fracture due to creep with fracture under a rapidly applied load as to the possibility of removing or repairing the part before complete fracture occurs.

5. Does wood creep? State evidence for your answer.

6. In a creep test of a copper-lead alloy at 110°F. the following values of creep, measured in per cent of length, were obtained. Using the method shown in Fig. 19, determine the limiting creep stress for 0.25 per cent creep in 1 yr.

Time, hr.	Tensile stress, lb. per sq. in.				
	50	100	150	200	250
0	0	0	0	0	0
50	0.005	0.007	0.010	0.022	0.045
200	0.006	0.008	0.016	0.026	0.055
400	0.007	0.009	0.023	0.039	0.075
800	0.008	0.011	0.030	0.050	0.108
1,200	0.010	0.015	0.037	0.062	0.145
1,600	0.011	0.017	0.045	0.080	0.175
2,000	0.013	0.020	0.050	0.090	0.205

7. Why is the elongation at fracture less for long-time creep tests than for short-time tests?

8. If you were asked to state the tensile strength at 1200°F, of the steel whose test results are shown in Fig. 22, what would you answer?

9. In which of the following structural or machine parts would the danger of fracture under creep be greater than the danger of structural damage due to deformation under creep: (1) Flange bolts in a high-temperature steam line, (2) lead sheathing on an electric power cable, (3) the blades of a gas turbine, (4) a plain concrete retaining wall, (5) a reinforced-concrete column, (6) the water tubes in a steam boiler, (7) a steel column exposed to high temperature, (8) stay bolts in a boiler, (9) a spring used for measuring weight, accidentally exposed to high temperature for a long time, (10) a lead water pipe under pressure?

CHAPTER V

THE FAILURE OF MATERIALS BY FRACTURE

The General Nature of Fracture. Fracture of a structural or machine member may be pictured as the actual tearing apart of a portion or the whole of the member. Probably many, perhaps nearly all, structural or machine parts have many microscopic cracks scattered throughout them, especially near the surface. These microscopic fractures do not cause appreciable structural damage unless they *spread* under long-continued steady load or under many cycles of repeated load.

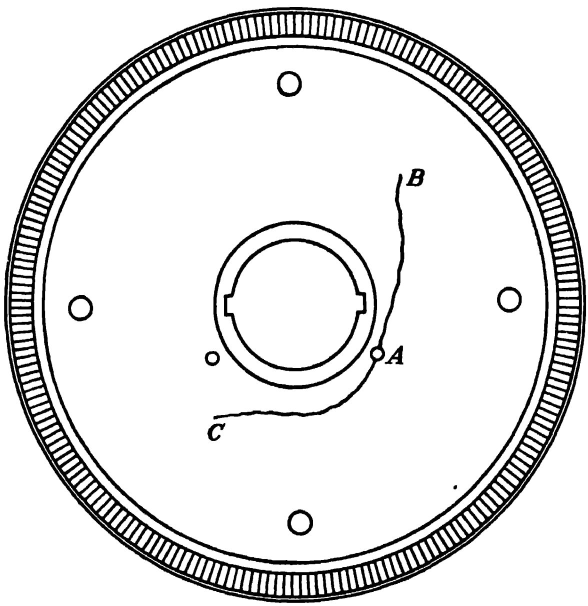
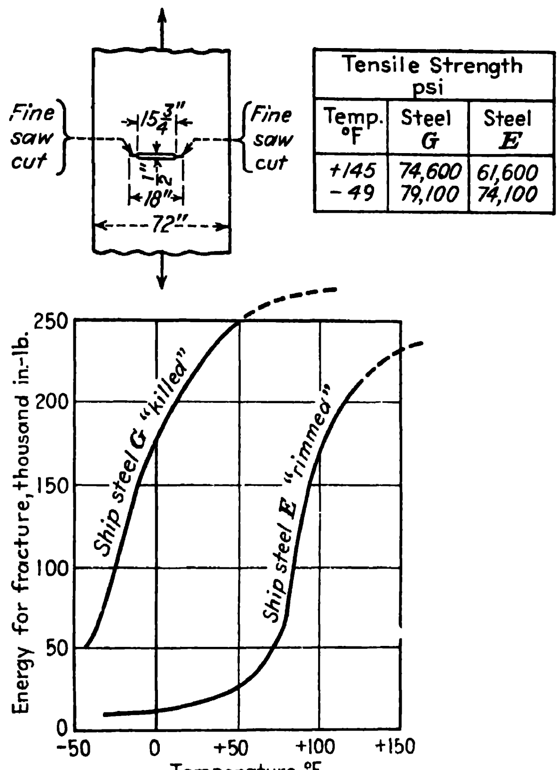


FIG. 23. Spreading crack in steam turbine disk. Crack started at hole A and spread to B and to C.

Sometimes a localized spreading fracture can be detected in a structure or machine member before disastrous complete fracture occurs (see Fig. 23) but in many cases this cannot be done, and fracture as it occurs is sudden, disastrous, and without warning.

Fracture under Static Load, Effect of Temperature. Under heavy loads applied slowly for a few times at room temperature, ductile materials usually show evidence of slip which does not become fracture unless

there is a distinct "necking down" under tension, indicating a state of flow in the materials. Brittle metals sometimes show signs of slip, but they usually fracture without signs of any appreciable flow of the material. Machine and structural parts made of ductile material, and in which there are sudden discontinuities in cross section (sharp shoulders, holes, notches, etc.) behave somewhat like parts made of brittle material, and the total distortion before fracture is small, although the tensile



Tensile Strength psi		
Temp. °F	Steel G	Steel E
+145	74,600	61,600
-49	79,100	74,100

FIG. 24. Energy-temperature diagrams for fracture of two specimens of ship plate l under static load. (*Courtesy of W. M. Wilson.*)

strength may be but little, if any, less than that of an unnotched part made of the same material.

Such fracture of nominally ductile metal is most likely to take place under low temperatures, as was the case in the sudden fractures of steel ship plates in ships in the Northern Pacific during the Second World War. Fracture tests under low temperatures were made of ship plates at the University of California and the University of Illinois on specimens 72 in. wide and 0.75 in. thick.

The specimen and the results of two typical tests of steel are shown in Fig. 24. The fractures of ship plate in service started at some sharp corner of a slot or other hole in the plate. At such a sharp corner, there is a high concentration of stress, as is discussed in Chap. VII. Under a single load (or a few loads), the ductility of the plate at the notch is very small and the spread of a fracture from the slot depends on the temperature and the type of steel.

In the specimens tested, very high stress concentration was caused by a fine saw cut at each end of the slot in the test specimen. It is seen that, for both specimens, the tensile *strength* actually increased slightly as the temperature decreased but that the *energy* required for fracture *decreased* very greatly. It will be noted that the specimens of steel E showed a rapid loss of energy for fracture below 110°F. Steel E was not deoxidized and is known as "rimmed" steel. Steel G was deoxidized with aluminum during its manufacture and is known as "killed" steel. The specimen of steel G did not show a rapid loss of energy for fracture until the temperature had dropped to 0°F., or approximately to that value. Steel G is said to have a lower *critical temperature* for brittleness than steel E.

Tests of critical temperature for brittleness are also made on small specimens with a sharp notch in the specimen, and the energy required to fracture the specimen is determined by the fall and rise of a heavy pendulum which strikes the specimen, fracturing it by bending. This "impact test" is described in Chap. XVIII.

Damage by Inelastic Action. Permanent deformation of a considerable volume of material is a rather common cause of structural damage to structural and machine parts in service. Such damage may so distort a structural or machine part that it must be replaced, but such damage is most dangerous when it leads to compressive buckling of columns and thin plates. Buckling of parts and fracture under repeated shearing or tensile stresses are the two great causes of *structural disaster* during the erection and the subsequent use of the structure or machine.

Fracture under Repeated Stress, "Fatigue" of Metals. About 80 per cent of the failures of machine parts in service is caused by repeated stress or, as it is rather inappropriately called, "fatigue" of metals. Under repeated stress, even metals ductile under a single load fracture, not only at stresses below the tensile strength but sometimes at stresses which are below the yield strength of the metal. The fracture under cycles of repeated stress shows very few indications of ductility (see Figs. 23 and 25). The surface of the fracture is usually rough and "crystalline" in appearance, with a small area of smooth metal. Figure 26 shows typical fractures under repeated stress. From the rough "crys-

talline appearance of a considerable part of the fracture it was natural, in the days before the metallographic microscope, to assume that the metal had "crystallized" under repeated stress and had fractured along the surfaces of the "crystals." When Ewing, Rosenhain, and Humfrey, at the end of the nineteenth century, examined fractures with the aid of the metallographic microscope, they found that after a few cycles of stress, "slip lines" appeared (see Fig. 13). Figure 27, taken recently with an electron microscope, shows these slip lines in more detail. Under succeeding cycles of stress, cracks may start and, for a number of cycles of

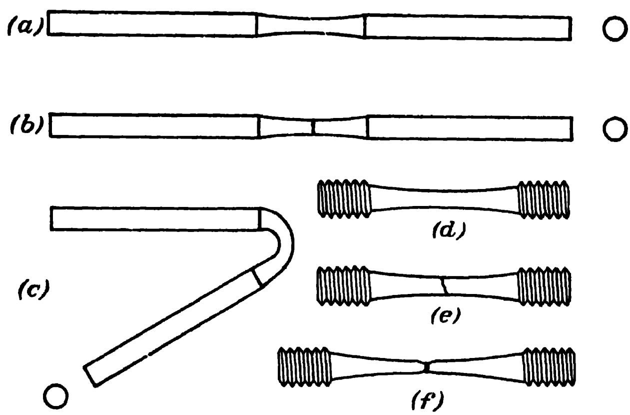


FIG. 25. Test specimen after single-load test and after fatigue test: (a) original flexure specimen; (b) specimen fractured by repeated cycles of reversed flexure; (c) specimen bent by single load; (d) original tension specimen; (e) specimen fractured by repeated cycles of tension; (f) specimen fractured by one slowly applied load.

stress, spread in the direction of the slip lines, which is approximately in the direction of the maximum nominal[1] shearing stress. If the crack spreads to fracture it frequently changes its direction to a direction at right angles to the principal nominal tensile stress. Figure 28 shows a crack at a very early stage, following quite closely the direction of the slip lines in the metal.

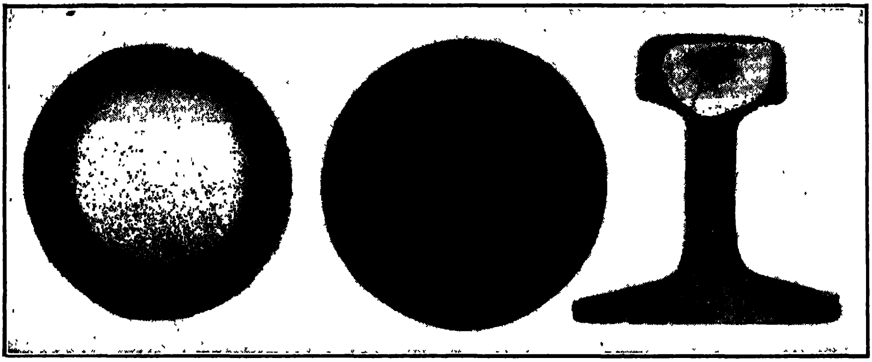
Today the crystallization theory of fatigue of metals has been discarded and a theory of progressive fracture has been generally accepted. However, the rather misleading name, "fatigue" of metals, is still in common use.

The smooth surfaces of the fractures (see Fig. 26) show the surfaces over which a fatigue crack has spread. As the crack spread and successive cycles of stress were received, the surfaces of the crack were rubbed

[1] The term "nominal" applied to a stress indicates the stress as computed by the common formulas of mechanics of materials.

smooth. The rough surfaces are those on which there was a sudden final fracture with very little rubbing action.

The difference in a failure of material under a single load (or a very few loads) and under oft-repeated load may be summed up as follows. Under a single load, the material either withstands the load or it fails. Under repeated load, local stresses and strains, which would be of no importance if only one loading were applied, may form a nucleus for damage which, under repeated stress, spreads until the whole member fails (see also footnote on page 76, Chap. VI).



a b c

FIG. 26. Surfaces of different types of fatigue cracks spreading to complete fracture: (a) fracture starting at the circumference of a round shaft and spreading in toward the center; (b) fracture starting at one side and progressing toward the opposite side of a shaft; (c) fracture in railroad rail starting from crack caused by too-rapid cooling and spreading over the light-colored area. Then complete fracture occurred.

Fracture under Repeated Load Compared with Fracture under Static Load. In computing the resistance of materials to fracture under a single load (or a few loads), the common formulas of mechanics of materials, such as are given in handbooks and in elementary textbooks, may be used and probable stress for fracture computed with a fair degree of accuracy from the results of *static* tests of specimens. However, those common formulas are based on three assumptions: (1) the material is homogeneous, (2) the material is isotropic, equally stretchable or compressible in all directions, and (3) Hooke's Law (stress is proportional to strain) holds.

An examination under the microscope of any of the common structural materials (excepting glass and some plastics) shows that the material is *not* homogeneous. Most metals are made up of thousands of crystalline grains of different sizes and shapes, and these crystalline grains are much weaker in some directions than in others. Wood and some textiles are made up of longitudinal elements and the stiffness and

strength in different directions is by no means the same; the material is not *isotropic.* As deformations (stretch, shortening, bending, twist) are measured with instruments of greater sensitivity, minute deviations from Hooke's law occur at lower and lower stresses. Probably, some

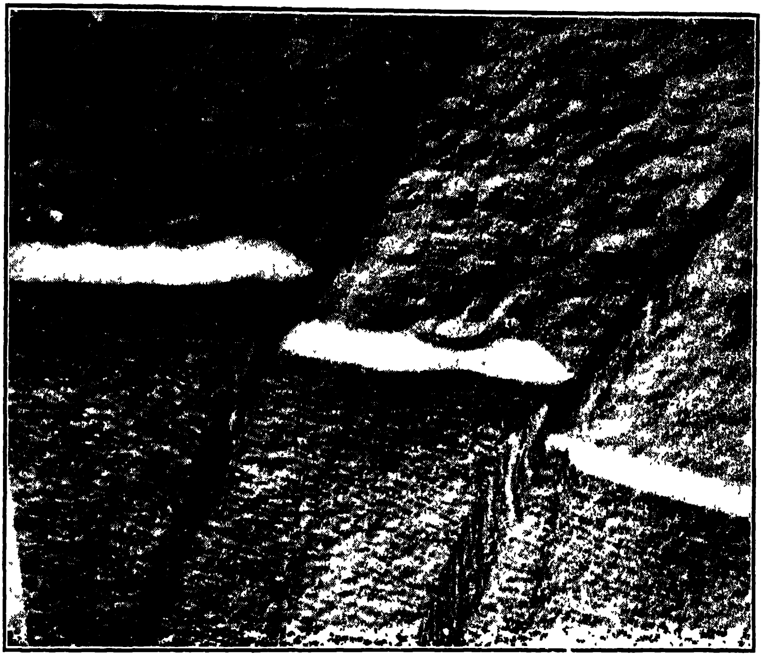


FIG. 27. Electron micrograph of deformation marks (commonly called slip lines or slip bands) in a specimen of armco iron (very low-carbon steel). An electron micrograph shows the surface of a parlodian replica after the replica has been removed from the surface of the specimen. The electron micrograph is most clearly understood if it is remembered that the *under* side of the replica is photographed, and that hollows in the surface of the metal specimen appear as humps in the electron micrograph. In this micrograph deformation marks indicate some sliding of metal along the surface, as is shown by the breaks in the grain boundary between two crystalline grains (grain boundary shown in white in the micrograph), and some vertical displacement is shown by shadows cast by deformation marks in the upper crystalline grain. Vertical displacement is also shown in the lower crystalline grain, but less clearly than that in the upper grain. Magnification 18,000 times. (*Electron micrograph by William J. Craig in the electron microscope laboratory, University of Illinois.*)

localized inelastic action on a microscopic scale occurs under almost any load which is applied to a structural or machine member.

How, then, do we dare to use the common formulas for strength of materials, and the "nominal" stresses computed by their use, to design structural and machine members to withstand steady load? This is partially explained by the fact that in using these formulas we usually make another assumption, rarely stated in textbooks and handbooks—

the assumption that whenever, *at any point* in a structural member or a machine part, inelastic action takes place or a minute crack is opened, then that member *has failed* and cannot be safely used. Now it is doubtful if, for example, there is in service a riveted or a bolted joint in which there are *no* minute regions which have not suffered inelastic action—inelastic action around the bearings of rivets and bolts and in the screw threads of bolts—inelastic action or perhaps microscopic cracking which does not spread under a few static loads. Probably this is true even for "creep" loads and repeated loads but a much smaller volume of material is required to start injurious creep after many days, or a destructive crack under repeated loads, than the volume necessary to cause appreciable structural damage under a static load. Perhaps, looking back at Fig. 24, it may be necessary to modify this statement for metals at a very low temperature and for very brittle materials. Such materials can do very little readjusting of the stress in the region around a microscopic permanent stretch or even a microscopic crack so as to avoid fracture. Metals which have the ability to stretch, bend, or twist appreciably before a crack starts spreading may be said to have a high "crackless plasticity."

Under static loads at temperatures which are too low to cause appreciable creep, the common formulas for strength of materials for design purposes can be used. Even then, care must be taken to watch for the decrease of "crackless plasticity" which may be caused by a sharp notch, a small hole, or a sharp fillet—that is, by any "stress raiser." This matter is discussed more fully in Chap. VII.

Even if the common formulas for stress and strain are not a complete and safe guide for design of structural and machine members, they usually give a reliable indication of the region in which structural damage is most likely to occur.

Under repeated cycles of applied load or moment, the danger of damage *spreading* from a minute overstressed area is always present. At minute areas of localized stress, there is a tendency for slip (see Figs. 12 and 13); then for a crack to form and *spread* (see Fig. 28). Just when and how a crack starts and whether or not it will spread to fracture depends on the localized high stress over a small area, a stress which may be several times as large as the nominal stress at that area. Then, when once a crack is started, its progress depends on the nature of the successive grains of metal it attempts to invade. It may be stopped by "road blocks" of strong crystalline metal, or it may find "easy going" in regions of weaker metal, or in groups of crystalline grains which are so oriented that the crack easily passes from one to the next. There is no known formula for strength of materials to compute either the localized

high stress or the resistance which the crack, once started, will meet in its progress. Some cracks *stop* after a short travel, especially if they spread into regions where the nominal stress is low. Other cracks go further, their progress becomes accelerated, and they spread to complete fracture of a machine or structural member.

Under repeated stress it seems quite possible that two contradictory actions take place at the ends of a crack:

1. The crack tends to spread owing to the stress concentration at its end.

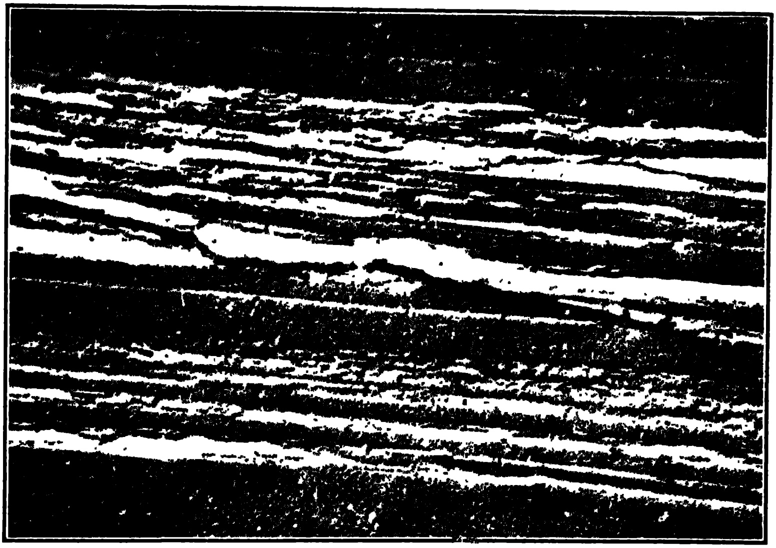


FIG. 28. Electron micrograph of a fatigue crack in cartridge brass at an early stage of its development. Note that the slip lines (deformation marks) are shown in white since the electron micrograph shows the *under* side of the parlodian replica. The parlodian is shoved into the crack and broken off, leaving a small projection which casts a shadow and outlines the direction of the crack. Note that in this case the crack at this very early stage is following closely the direction of the slip lines. Magnification 10,000 times. (*Micrograph by William J. Craig.*)

2. For cases of a cycle of stress which does not include reversal of stress (and possibly for some cases of reversed stress) the end of the crack tends to become blunter, more rounded, thus tending to diminish the stress concentration. The progress of a crack, perhaps the actual stopping of its spread before complete fracture, may be pictured as depending to some extent on the resultant effect of these two contradictory actions.

Fatigue Tests of Specimens of Metals. The strength of a *material* to resist cycles of repeated stress without fracture for a given number of cycles of stress may be determined with a good degree of reliability by

tests of specimens of the metal in repeated-stress testing machines. It is to be specially noted that the results of such a series of tests give the strength of the *material* and not necessarily the strength of a structural or machine part made of that material. In the process of making a machine part out of that metal, the strength may be affected by cold-working, heat-treating, "stress raisers" in the finished part, surface conditions of the part, etc. The strength under repeated stress of machine and structural parts is discussed in Chap. VII.

Some Symbols and Definitions used in Fatigue Testing. The following symbols and definitions follow closely those in the "Manual of Fatigue Testing," published by the American Society for Testing Materials, Philadelphia, Pennsylvania.

SYMBOLS USED IN FATIGUE TESTING

Symbol	Term	Symbol	Term
A	Area of cross section	P or W	Load
C	Cycle ratio	M	Bending moment
c	Distance from centroid to outermost fiber	T	Twisting moment (torque)
		R	Stress ratio
D or d	Diameter	S	Stress, nominal (tension or compression)
f	Frequency		
I	Moment of inertia	S_s or τ	Stress, shear
J	Polar moment of inertia	t	Time
n or N	Number of cycles	t or θ	Temperature

NOMENCLATURE FOR FATIGUE TESTING

Stress Cycle. The smallest section of the stress-time function which is repeated periodically and identically as shown in Fig. 29.

Nominal Stress, S. The stress calculated by the simple formulas of the mechanics of materials, such as $S = P/A$, $S = Mc/I$, or $S_s = Tc/J$, without taking into account the stress-raising effect of such discontinuities as holes, grooves, fillets, etc.

Maximum Stress, S_{max}. The highest algebraic value of stress in the stress cycle; tensile stress is considered + and compressive stress −.

Range of Stress, S_r. The algebraic difference between the maximum and minimum stress in one cycle. $S_r = S_{max} - S_{min}$.

Alternating Stress Amplitude (or Variable Stress Component), S_a. $S_a = S_r/2$.

Mean Stress (or Steady Stress Component), S_m. The algebraic mean of the maximum and minimum stress in one cycle. $S_m = (S_{max} + S_{min})/2$.

Stress Ratio, R. The algebraic ratio of the minimum stress and the maximum stress in a cycle. $R = S_{min}/S_{max}$.

Stress Cycles Endured, n. The number of cycles of stress which a specimen has endured at any given stage of a fatigue test.

Fatigue Life, N. The number of stress cycles which can be sustained without fracture for a given test condition.

S-N Diagram. A plot of stress against number of cycles to failure. It is usually plotted S *versus* $\log N$, but it is sometimes plotted $\log S$ *versus* $\log N$.

Cycle Ratio, C. The ratio of the number of cycles applied at a given stress level to the expected fatigue life at that stress level, based on the S-N diagram. $C = n/N$.

Fatigue Limit (or Endurance Limit), S_e. The limiting value of the stress below which a material can presumably endure an indefinitely large number of cycles of stress, the stress at which the S-N diagram becomes horizontal, and appears to remain so. Certain materials do not show a definitely established endurance limit, even after some hundred millions of cycles of stress.

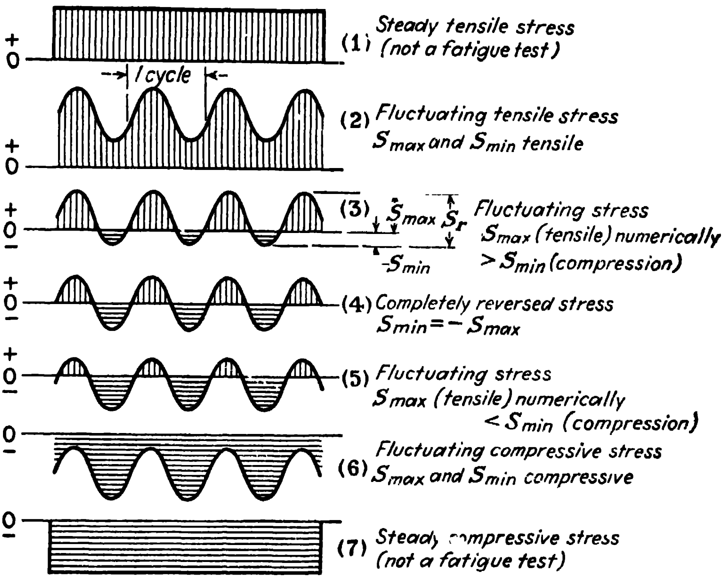


FIG. 29. Types of stress cycles.

If the stress is not completely reversed, it is necessary to state what is meant by the endurance limit. It may be expressed in terms of the alternating stress amplitude and the value of the mean stress, in terms of the maximum stress and the stress ratio, in terms of the alternating stress amplitude and the minimum stress. In this book the endurance limit is usually expressed in terms of the maximum stress, S_{max}, and the stress ratio, R.

Fatigue Strength, S_n. The greatest stress which can be sustained for a given number of cycles without fracture. The number of cycles should always be given. The same considerations as given under *Fatigue Limit* apply where the mean stress is not zero (stress not completely reversed during a cycle).

Fatigue Ratio (or Endurance Ratio). The ratio of endurance limit S_e or fatigue strength S_n to the static tensile strength, S_u; that is, S_e/S_u or S_n/S_u.

Fatigue Testing Machines. The strength of a metal to withstand without fracture cycles of repeated stress may be determined by tests

of specimens in repeated-stress testing machines. Again let it be noted that the endurance limit determined for fatigue specimens is not necessarily the same as the fatigue strength of structural or machine members made of that metal. For such members, surface conditions, residual stress, stress raisers, etc., will affect the fatigue strength.

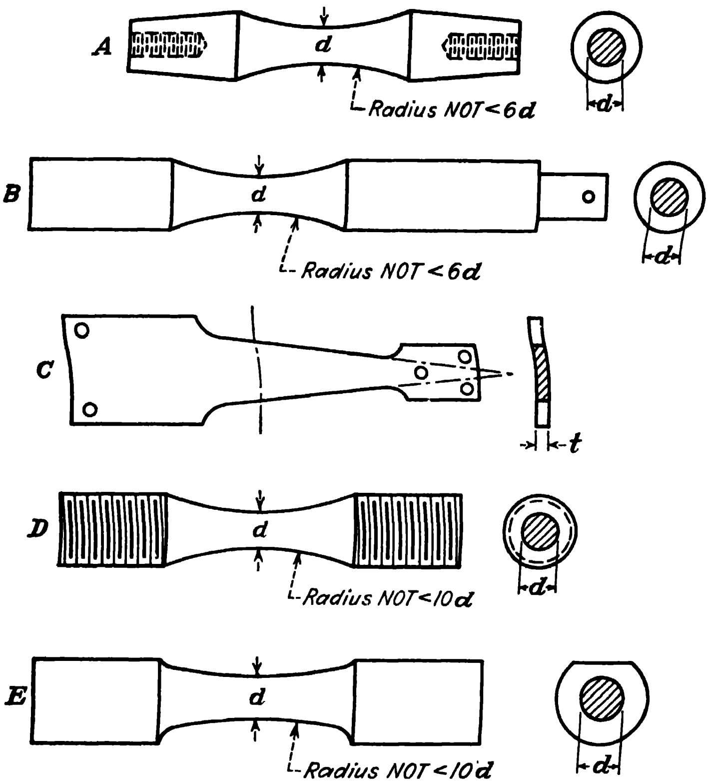


FIG. 30. Types of fatigue specimens: A, rotating-beam specimen (reversed flexure); B, rotating cantilever beam specimen (reversed flexure); C, plate or sheet vibratory specimen (any stress ratio R); D, tension-compression ("push-pull") specimen (any stress ratio R); E, torsion-fatigue specimen (any stress ratio R).

Figure 30 shows various types of test specimen for fatigue tests and Fig. 31 shows several types of fatigue testing machines. Test specimens for tests of the *metal* have no sharp stress raisers. The surface of the specimen is polished. While the actual, localized, microscopic-scale stresses, which start and spread a crack to fracture, cannot be computed by any of our common formulas (or by any formula using the theory of elasticity), these microstresses may be regarded as being roughly *proportional* to the nominal stresses at a location, and fatigue fracture occurs

in a region which is under maximum nominal stress, which is tensile or shearing in nearly all cases.

Figure 31(*a*) shows, in diagram, a rotating-beam testing machine with two equal bending forces $W/2$ applied to the specimen. The maximum bending moment applied to the specimen is $(W/2)a$. Figure 31(*b*) shows a cantilever rotating-beam testing machine in which the bending moment on the specimen is Wa. The moment and consequently the stress is varied by using different weights for both the rotating-beam machines. Rotating-beam machines cannot be easily adjusted to set up any other type of stress cycle than complete reversal, and no specimens except those with a circular cross section can be tested except at very slow speeds.

Figure 31(*c*) shows a vibratory type of fatigue testing machine in which the bending force is measured either by the deflection of the specimen, or by the vibration of a flat steel spring bolted to the end of the specimen and supported in the vise V. The adjustable-throw crank C determines the deflection of the specimen and the machine may be calibrated by standard weights as shown in Fig. 31(*d*). The moment Wa is proportional to the deflection of the specimen after it has withstood a few thousand cycles of stress. The deflection of the specimen is measured by the micrometer dial M, and calibration of the machine should be made at the beginning of the test, after a few thousand cycles of stress, and occasionally after that until the specimen fractures or the test is stopped.

Figure 31(*e*) shows a tension-compression fatigue testing machine which is operated by an adjustable-throw crank C, and the range of stress is controlled by the nuts N and N'. The deflection of the lever L is a measure of the tensile and compressive forces applied to the specimen S, and this deflection is measured by the micrometer dial gage M.

Figure 31(*f*) shows a fatigue testing machine for bending tests, which can be equipped for torsion tests or for light loads in tension and compression A small weight at an adjustable distance from the center of the drive shaft O causes reversed bending stress on the specimen. However, by putting a steady load on the specimen by the screw T and the calibrated spring G, the type of cycle of stress is changed. The machine may be calibrated by the deflection of an elastic specimen as the speed of the machine and the distance m are varied.

An investigation sponsored by the A.S.T.M.[1] showed in a general way that the endurance limit obtained by the different types of bend test fatigue machines gave slightly higher values for endurance limit than

[1] See reference 5(*a*) at the end of this chapter.

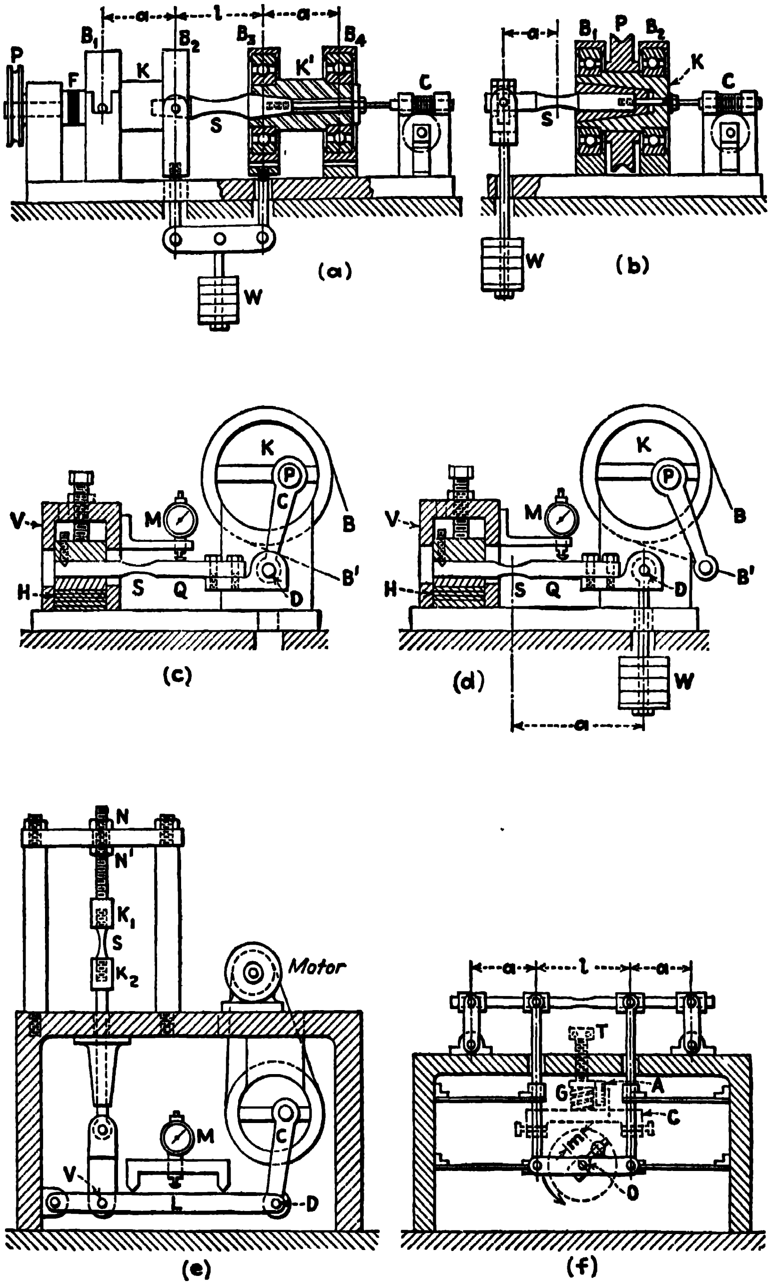


FIG. 31. Typical repeated-stress testing machines. Note in (c) and (d) plunger of dial gage M is kept out of contact with the specimen when machine is running.

did tension-compression (push-pull) machines. The variation found in this investigation was not greater than about 10 per cent. However, endurance limits were distinctly affected by the shape of the specimens used. In repeated-bending tests, higher values of endurance limit were found for round specimens than for flat specimens, or even for square specimens, of the same metal. The difference in endurance limit was as great as 16 per cent in some cases.

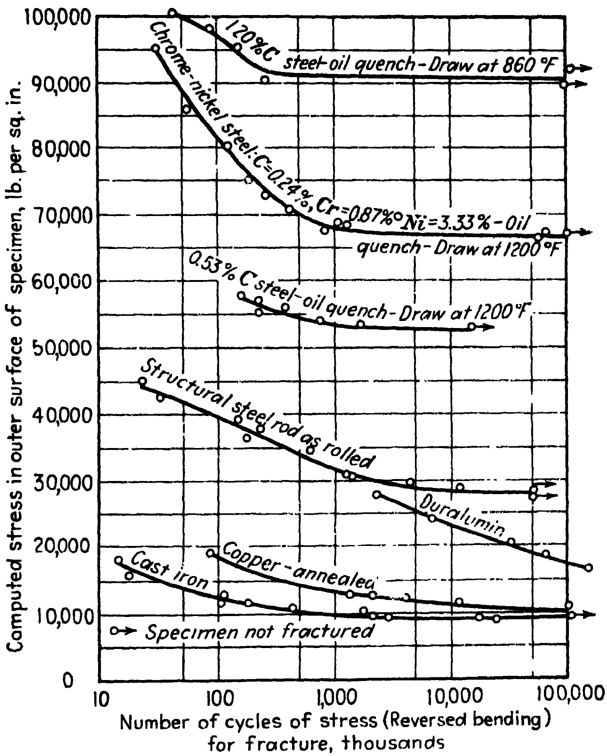


FIG. 32. Typical S-N (stress-cycle) diagrams for fatigue tests of various metals.

Figure 32 shows characteristic *S-N* diagrams for a number of metals. The endurance limit (fatigue limit) is located at the stress (S_{max}) for which the *S-N* diagram becomes horizontal. In Fig. 32, for all the metals shown, except copper and duralumin, the *S-N* diagrams become horizontal as nearly as can be determined from the data, thus indicating a limiting stress for endurance under an indefinitely large number of cycles of stress. The *S-N* diagram for copper becomes nearly horizontal.

Short-time Tests for Fatigue Limit. The determination of fatigue limit (endurance limit) as outlined in the preceding paragraphs is a

time-consuming and a costly test. Many attempts have been made to devise a short-time test for endurance limit. Some of these proposed tests have proved fairly reliable for ferrous metals, and for some non-ferrous metals, but none of them so far has proved successful for all metals tried.

However, for certain structural and machine parts, the probable number of high stresses in a normal period of service may be enough to make failure by progressive fracture the greatest danger, but may *not*

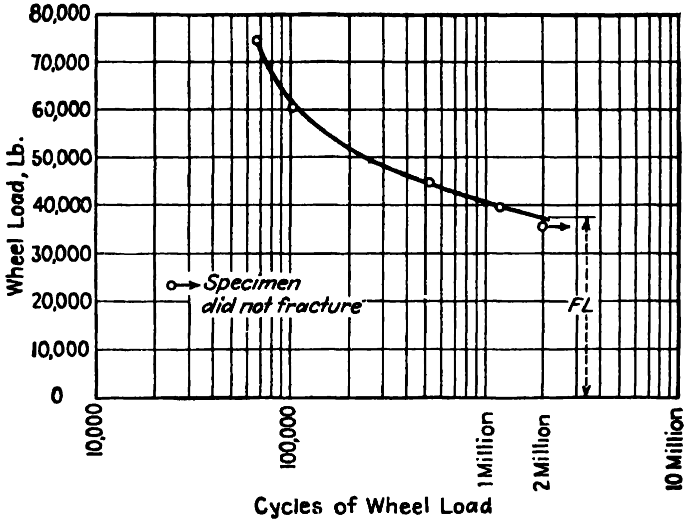


Fig. 33. Determination of fatigue strength of a gas-welded railroad rail for a fatigue life of 2,000,000 cycles of wheel load, 37,000 lb. wheel load.

be as large as 10,000,000 cycles of stress. Most structural members in steel bridges are called on to withstand only a few hundred thousand cycles of heavy stress before they are discarded or reinforced; moreover, *heavy* stresses occur at rather long intervals of time, and a fatigue crack can be detected before fracture is imminent. Boiler shells and pressure vessels usually have to withstand something like 100,000 cycles of stress before they are discarded or reinforced. Railroad rails may be expected to be subjected to some 100,000 cycles of abnormally high wheel load before they *wear out* and new rail has to be put in their place.

Figure 33 shows the determination of the repeated (but not reversed) load for a *fatigue life* of 2,000,000 cycles of stress, varying from zero to a maximum during a cycle. The load was 37,000 lb. The number of cycles of stress required for fracture under a given stress level might also be taken as a basis for design. If this is done, however, the "factor of safety" for number of cycles of stress for fracture under a given stress

range should be *very much higher* than the factor of safety for the stress range for a number of cycles of stress.

This may be seen in the S-N diagram in Fig. 34 (remembering that N is plotted to a logarithmic scale). Figure 34 shows the results of fatigue tests of specimens of structural steel with 20 specimens tested at each of three stress levels all *above the endurance limit* of the metal. There are very large variations in the number of cycles of stress required

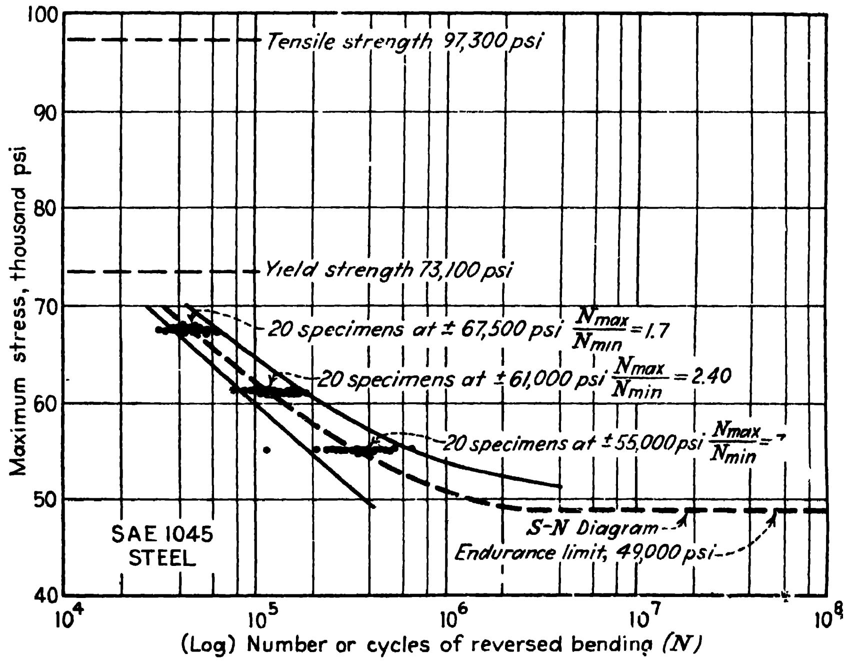


FIG. 34. S-N diagram showing "scatter" of number of cycles for reversed bending for fracture at three stress levels above the endurance limit (fatigue limit). Material, S.A.E. 1045 medium-carbon steel. (*Courtesy of Prof. T. J. Dolan.*)

to cause fracture at any given stress level. For example, under a maximum repeated stress range of ±61,000 lb. per sq. in., the minimum life for 20 specimens was about 80,000 cycles and the maximum life was about 190,000 cycles, a variation of 240 per cent. Now, a reduction of 10 per cent from 61,000 to 55,000 lb. per sq. in. reversed bending stress would increase the *minimum* fatigue life to about 190,000 cycles, which is about the *maximum* fatigue life for 61,000 lb. per sq. in. stress. That is, a reduction of 10 per cent in maximum stress for this metal means an *increase* in fatigue life of 140 per cent. From the test data now available, it seems it is more satisfactory to base design of parts to be subjected

to repeated stress on *stress for a given fatigue life* than on *fatigue life for a given stress.*

Endurance Limit in Shear. Tests in repeated or reversed torsion are the most used for determining of endurance limit (fatigue limit) in shear. For ductile metals the endurance limit under cycles of reversed *shearing stress* is about 55 per cent of the endurance limit under reversed *bending stress.* Under cycles of nonreversed stress, either in flexure, in tension-compression, or in shearing stress, the endurance limit developed is discussed more fully on page 62.

In tests under tensile load, compressive load, or bending moment, there are always developed three principal stresses perpendicular to each other, as well as shearing stresses on inclined cross sections of the specimen or piece under test. The maximum shearing stress developed is equal to one-half the algebraic difference of the maximum principal stress and the minimum principal stress.

In tests under an axial tensile load or under a compressive load, or in bending tests, the maximum principal stress is equal to P/A, or Mc/I, and the minimum principal stress *at the surface* is zero, so that the maximum shearing stress *at the surface* is half the principal tensile (or compressive) stress.[1] Under torsion there are four stresses, each of the same magnitude: (1) a longitudinal shearing stress, (2) a circumferential shearing stress, (3) a tensile stress at 45 deg. with the axis of the specimen, and (4) a compressive stress at right angles to the tensile stress.

In most ductile metals, fatigue fracture in torsion usually starts in the direction of the longitudinal shearing stress, if the direction of rolling of the metal is parallel to the axis of the specimen, and starts in the direction of the circumferential shearing stress, if the direction of rolling is at right angles to the axis of the specimen.[2]

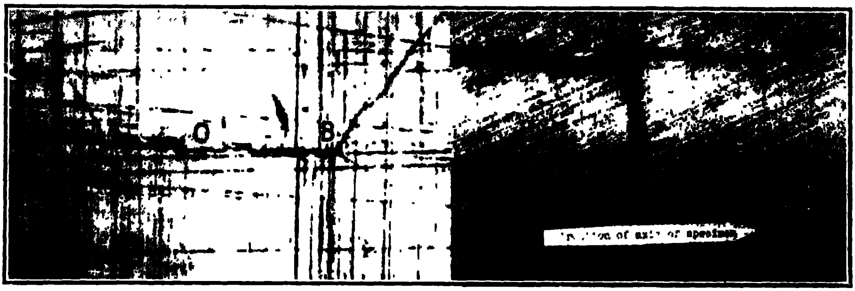
Figure 35(*a*) shows such a fatigue crack in structural steel which started as a longitudinal crack in the direction of a principal shearing stress, but before complete fracture changed its course to a direction at 45 deg. with the axis and at right angles to the principal tensile stress. This is the common type of torsion-fatigue fracture for rolled metals, rolled parallel to the axis of the specimen. Sometimes, though rarely, such specimens show circumferential shear cracks and a report has been

[1] Below the surface the stresses are more complex, but as fracture nearly always starts at the surface (unless the surface is specially hardened by heat-treating or by cold-working) these subsurface stresses are not considered here.

[2] In the case of some brittle metals, especially of gray cast iron, the shearing strength is greater than the tensile strength, and the fracture of a torsion specimen takes place along the direction of maximum tensile stress, at about 45 deg. with the axis of the specimen.

given of specimens with axis at right angle to the direction of rolling which have developed circumferential cracks to final fracture.

Figure 35(*b*) demonstrates a fatigue fracture of a specimen of an aluminum alloy which shows shearing fracture both longitudinally and circumferentially. Since, in a torsion specimen, the maximum tensile stress is developed in a diagonal direction and is much smaller than the tensile stress required to produce fracture in a bending fatigue test, it seems reasonable to consider the torsion fatigue fracture as starting in the direction of one of the two maximum shearing stresses.



a *b*

FIG. 35. Origin and direction of spreading fractures in two specimens tested under cycles of reversed torsion.

(*a*) Test of a structural steel specimen, axis in the direction of rolling. Fatigue failure started at *O* and proceeded in a direction approximately parallel to the axis, in the direction of the maximum shearing stress (axial) to *A* and *B* where the direction became approximately at right angles to the maximum tensile stress.

(*b*) Test of an aluminum alloy specimen with axis parallel to the direction of rolling. Fatigue fracture started, presumably at approximately the center of length, and spread in the general direction of *both* maximum shearing stresses, axial and circumferential.

Endurance Limit under Repeated Compressive Load. A fatigue fracture is a spreading crack, and the opening of the crack seems to imply some tensile stress. This is probably true, but the crack in its early stages is microscopic and that stress cannot be determined by the common formulas for nominal stress.

However, fatigue cracks have been developed to fracture in specimens under cycles of compressive axial loading. The initial direction is nearly always along a slip line (see Fig. 28). These cracks sometimes start as diagonal cracks along a plane of maximum shearing stress, but sometimes take a direction at right angles to that of the compressive load. All fatigue cracks developed under axial compressive load so far tested at the University of Illinois have developed cracks or fracture only under direct stresses greater than the yield strength of the metal (offset = 0.1 per cent). This suggests that the importance of fatigue failures under axial compressive stress is not very great, since it is rarely,

if ever, allowable to permit working stresses greater than the y· strength of a metal.

Beyond the yield strength, the uniformity of stress distribution is probably broken up, and on the various vertical elements of the specimen inelastic stress is not at all uniformly distributed. On the *release* of load, the more deformed vertical elements will hold back the complete recovery of length of the less deformed elements and tensile stresses will be set up. Probably such tensile stresses are not uniformly distributed along the longitudinal elements of the specimen, and considerable stress concentration may be present so that high tensile stresses may be set up locally on release of a compressive load which has been stressed above the yield strength.

Gray cast-iron compression specimens fail along diagonal planes where shearing stress is a maximum, and some brass compression specimens and aluminum specimens also fail along planes of maximum shearing stress. As noted above, steel specimens under repeated compression usually fail approximately at right angles to the axis of the specimen.

Effect of Range of Stress on Endurance Limit. For repeated axial or flexural stress, setting up *partial*, but not complete, reversal of stress during a cycle, the following empirical formula, based on many series of fatigue tests, has been found to give safe values for iron and steel values of R from -1.0 to $+0.25$.

$$\frac{S_e}{S'_e} = \frac{3}{2 - R} \tag{1}$$

in which S'_e is the endurance limit (fatigue limit) for cycles of completely reversed stress, R is the stress ratio and S_e the fatigue limit (see pages 52 and 53).

For aluminum and aluminum alloys, the formula

$$\frac{S_e}{S'_e} = \frac{2.25}{1.25 - R} \tag{2}$$

seems to give better results for cycles of bending stress. This formula is based on test data given in the 1938 edition of the "Structural Aluminum Handbook" published by the Aluminum Company of America.

The few test data for cast iron and for copper alloys give results not widely different from those given by equation (1).

For the effect of range of stress under repeated torsion, the shearing stresses are the most important, at least for ductile metal. The fatigue limit (endurance limit) for shearing stresses, also based on test data, is given with a good degree of reliability by the equation

$$\frac{\tau_e}{\tau'_e} = \frac{2}{1 - R} \tag{3}$$

in which τ'_e is the endurance limit for cycles of completely reversed shearing stress and τ_e is the endurance limit for cycles of shearing stress with the stress ratio R.

These three formulas may be safely used *if they give values below the yield strength of the material.* If, however, they give values above the yield strength of the material, the danger of failure or serious structural damage by inelastic action is greater than the danger of failure by

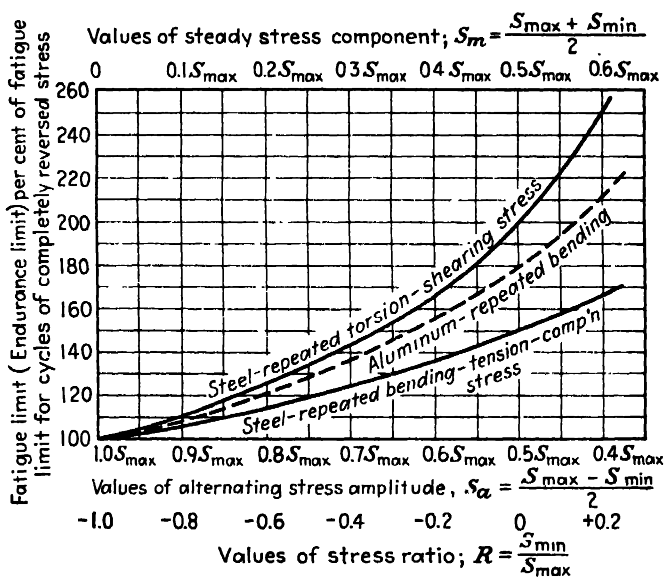


FIG. 36. Fatigue limits for various values of steady-stress component, alternating stress amplitude, and stress ratio. For complete reversal of stress in cycle, $R = -1.0$.

progressive fracture, and the *yield strength* is then to be used as a limiting stress rather than the fatigue limit.

Figure 36 shows graphically the results of equations (1) to (3). In addition to giving results in terms of fatigue limit and stress ratio R, scales for values of alternating stress amplitude S_a and of steady stress component S_m are also shown so that results may be expressed in several different ways (see pages 52 and 53 for definition of the above terms).

There is some evidence that when machine or structural parts are subjected to cycles of fluctuating (but not reversed) stress, the effect of stress concentration at notches, holes, keyways, etc., is measured by the alternating stress amplitude S_a (rather than by the stress ratio R).

Effect of Speed of Testing. Today the most convenient method of shortening the determination of the endurance limit is the use of high-speed fatigue testing machines. Machines with a speed of 12,000 cycles of stress per minute are on the market and tests have been made at even higher speeds. Table III gives values of endurance limit determined in tests of small specimens at various speeds. The same type of testing machine was used for all tests. The effect of frequency of

TABLE III. EFFECT OF SPEED OF TESTING ON ENDURANCE LIMIT
All tests made on rotating-beam fatigue testing machines, by G. N. Krouse at the University of Illinois

Metal	Speed, cycles of stress per minute		
	1,500	10,000	30,000
	Endurance limit, lb. per sq. in.		
Structural steel	30,000	32,000	33,000
Rail steel	50,000	51,000	53,000
Heat-treated alloy steel (S.A.E. 4140)	91,000	91,000	93,000
Cast iron (gray)	10,000	10,000	11,000
Duralumin	15,000*	15,000*	16,000*

* Fatigue strength for 100,000,000 cycles of stress.

cycles of stress at room temperature is seen to be slight even for speeds as high as 10,000 cycles of stress per minute and it is not very great even for 30,000 cycles of stress per minute. However, at temperatures high enough to cause an appreciable "creep" in the metal the effect of frequency of cycles of stress may be very large (see page 67).

Chemical Composition, Heat-treatment, and Fatigue Strength of Steel. Available test data do not indicate that there is any alloying element which gives outstanding fatigue strength *directly* to steel. Certain alloying elements, among them nickel, chromium, vanadium, molybdenum, manganese, and silicon, *do* have a marked *indirect* effect on the static strength and the fatigue strength of heat-treated steel. If plain carbon steel is given a strengthening heat-treatment, the strengthening effect penetrates only a slight distance into the metal. However, if certain alloying elements are present, the penetration of the strengthening action of the alloy goes deeper. The use of alloy steels then makes possible the effective heat treating of larger pieces of metal than is possible with plain carbon steel. The use of alloy steel makes it possible to increase the variety and the range of size which can be effectively heat-treated under shop conditions.

Changes in Metal under Repeated Stress. Again it may be noted that when strength under repeated stress is considered, the very slight inelastic action which has been found at stresses below the yield strength has cumulative effects under successive cycles of stress (see Fig. 37). In a fatigue test of brass extending to nearly 3,000,000 cycles of reversed bending, H. J. Gough at the British National Physical Laboratory measured stresses and strains throughout a complete cycle for the first cycle, the second cycle, and successively under the 7th, the 128th, the 2,129th, and 264,130th, the 406,930th, and the 2,812,230th cycles. It will be noted that in the first cycle there was considerable inelastic

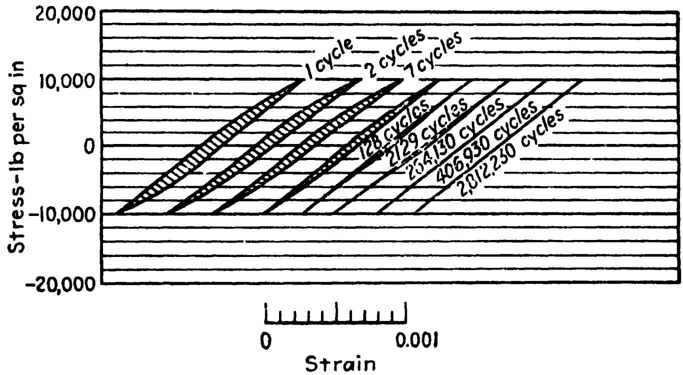


FIG. 37. Increase in elastic strength and loss of ductility of brass with increasing number of cycles of reversed bending. (*Test data from H. J. Gough.*)

action and considerable lost energy, as is shown by the area of the shaded portion of the stress-strain diagram. This lost energy is called *mechanical hysteresis* and it diminishes under successive cycles until after 406,930 cycles no mechanical hysteresis could be detected by the strain-measuring apparatus used. Evidently the elastic strength of the metal was increased. Just what is the cause of this increase of elastic strength under repeated cycles of stress is a matter about which there is much discussion.

This increase in elastic strength is said to be due to *cold-working* and two possible sources of increased elastic strength may be noted:

1. Under cold-working, there are found appreciable volumes of metal in which *compressive stress* has been set up. If this "residual" compressive stress is found, as it frequently is in a location which in service is subjected to repeated tensile stress or repeated shearing stress, the residual compressive stress would to some extent offset some of the tensile stress and diminish the "slip" due to any shearing stress in that region.

2. Under repeated cycles of stress, the crystalline grains tend to break

up by slip (see page 28) and then by cracking into smaller bodies. This is sometimes called "fragmentation" (a somewhat misleading term) and sometimes the still-cohering fragments into which the crystalline grain has been divided are called "crystallites." This division into crystallites furnished new boundaries at which progressing slipping and cracks may well be hindered in their progress.

In any event, up to a certain limit, cold-working does strengthen metals against elastic failure and, to a less extent, against fatigue fracture. The amount of strengthening is different for different metals.

However, cold-working can be overdone. The strength of the metal increases at a diminishing rate as cycle after cycle of stress is withstood, but the *ductility* of the metal is diminished. This diminution of ductility can be observed in making tests of pairs of specimens of brass or of structural steel. If one specimen of each pair has been hot-rolled and the other specimen cold-rolled after hot-rolling, the elongation at fracture in a tension test is less for the cold-worked specimen of the pair.

Under cycles of stress with a large stress range, loss of ductility may be expected to start a crack in some low-resistance region, a crack probably microscopic is size. However, as further cycles of stress are applied, other cracks form, and if the stress range is above the endurance limit, one or more of these cracks spreads, usually at an accelerated rate, and fatigue fracture suddenly takes place.

Just where the dividing line between too little and too much cold-work is found can at the present time be determined only by the "empirical" method of running enough tests to supply data for an S-N diagram. The spreading crack which causes fracture usually starts along a slip plane, but in its progress usually changes direction so as to be at right angles to the principal tensile stress in that region. In torsion tests in which the maximum shearing stress is as great as the maximum tensile stress, this change of direction of the spreading crack frequently occurs [see Fig. 35(a)], although sometimes in torsion tests the fracture continues along the line of a principal shearing stress, longitudinal or circumferential. In Fig. 35(b) there is a crack in the longitudinal direction and one in the circumferential. As such a crack spreads from grain to grain, it is never very far from the direction of some atomic plane in the metal, along which slip can occur.

Fatigue Strength under High Temperature. Under temperature high enough to cause appreciable *creep* in a metal, the strength under repeated stress is diminished. Creep under a steady load may, of course, take place without *fatigue* due to repeated stress, but *repeated stress at temperatures high enough to cause creep cannot be present without some creep.* Tests indicate that this holds even for cycles of completely reversed

stress, possibly because the slip planes and crack directions on *release* are not quite the same as during *application* of load.

One effect of this combination of repeated stress and creep is that at high temperatures the number of cycles of stress necessary to cause fracture is greater for high frequencies of cycles of stress than for low frequencies [see Fig. 38(*a*)]. The *S-N* diagram for the tests of a low-carbon steel at 200 cycles per minute is below the *S-N* diagram for tests of the same metal at 2,500 cycles per minute. If, instead of plotting

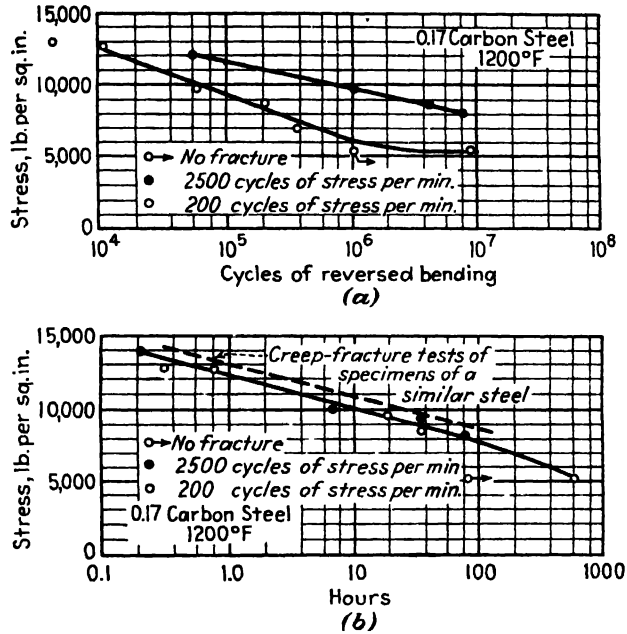


FIG. 38. *S–N* diagrams and stress-time diagrams of reversed-bending fatigue tests of plain carbon steel at 1200°F. and at frequencies of cycle of stress of 200 and 2,500 per minute.

an *S-N* diagram for these high temperature tests at 1200°F., a diagram is plotted with stress as ordinates and *time during the test* as abscissas [see Fig. 38(*b*)], then the test data of the tests at 200 cycles per minute and at 2,500 cycles per minute fall very closely along the same line. However, this is merely a coincidence, and Fig. 39 shows the results of tests of lead sheet tested at room temperature at four different frequencies of cycles. Lead creeps appreciably at room temperatures, and the effect of this creep is shown in Fig. 39(*a*) by the *increase* in the number of cycles of stress required for fracture as the frequency of cycles is higher.

However, when the results of the tests of specimens of lead are plotted on a stress-*time* diagram, the result is different from the results of tests

of low-carbon steel at 1200°F., as may be seen by comparing Fig. 38( ) with Fig. 39(*b*). For the lead, the higher the frequency of cycles of stress, the shorter the elapsed time before fracture and the greater the number of cycles of stress before fracture.

In Fig. 38(*b*) a line has been drawn showing the results of creep to fracture tests (with no repeated stress) of a steel with about the same

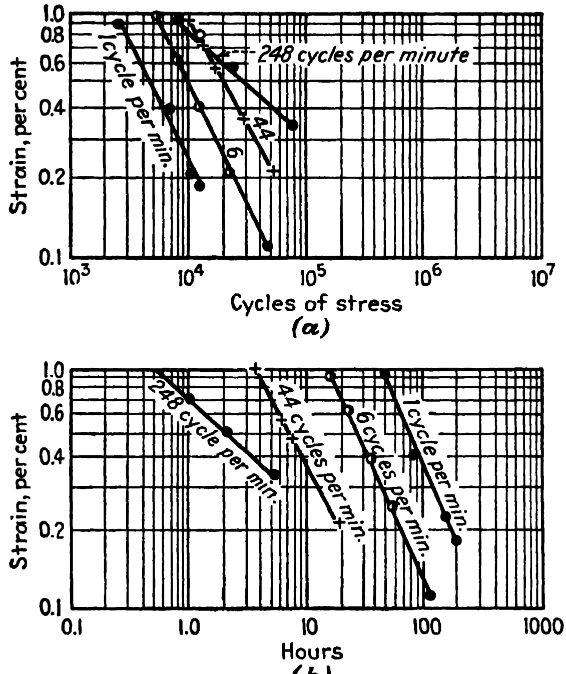


FIG. 39. *S–N* diagrams and stress-time diagrams of reversed-bending fatigue tests of lead sheet at room temperature (about 74°F.) and four different frequencies of cycle.

chemical composition as the 0.17 per cent carbon steel used in the fatigue tests at 1200°F. This line lies slightly above the line for the results shown by the stress-time diagram for the repeated-stress tests for the 0.17 per cent carbon steel. This seems to indicate that, under long-time service, the fatigue strength of a metal above the limit of appreciable creep approaches the creep-rupture stress for that metal when tested, or in service, under a steady load. However, much more investigation is needed in this field.

In general, it seems that fatigue fracture depends on *number of cycles of stress* and creep-rupture depends on *time under load*. Then, since for lead sheathing used on underground cables the frequency of cycles is

low (perhaps two or three cycles per day), the creep-rupture strength is the decisive factor.

Limiting Temperatures for Creep. It seems quite possible that all materials, at least all metals, creep slightly, even under loads which have been found satisfactory in service and even under room temperature. However, there are certain limiting temperatures below which creep is so slight as to be negligible for service conditions—so slight that only instruments of extreme sensitivity can detect the creep. Based on an examination of various reports of creep tests, the following temperatures, below which creep may be regarded as negligible, are suggested:

Cast iron	600°F.
Steel and wrought iron	800°F.
Brass and copper	400°F.
Aluminum	250°F.
Magnesium	Room temperature
Lead, tin, and zinc	below 32°F.

These figures should be regarded merely as estimates, and metal should be tested for appreciable creep under service conditions, whenever that is feasible.

Correlation of Fatigue Limit (Endurance Limit) with Other Properties of Metals. The fatigue limit of a metal seems to be more closely correlated with the tensile strength than with any other strength property of the metal. There seems to be some correlation between fatigue limit and Brinell hardness, but not so clear correlation as that with tensile strength. There seems to be very little correlation between endurance limit and yield strength of a metal. This is not surprising when it is remembered that yield strength marks a beginning (somewhat arbitrary) of serious slipping action within a considerable volume of metal, while fatigue failure and failure at tensile strength both consist of a *spreading* crack from some region of high stress.

Figure 40 is a correlation diagram between tensile strength and endurance limit for various metals. It is based on many test results, both static-tension test and reversed-bending fatigue tests. For rolled or forged iron, the fatigue ratio (endurance ratio) of fatigue limit (under reversed stress) to static tensile stress is usually between 45 and 50 per cent up to a tensile strength of about 200,000 lb. per sq. in. For steel castings, this fatigue ratio is about 40 per cent. For cast iron, it is about 40 per cent. For nonferrous metals, the fatigue ratio varies over a wide range from less than 25 per cent for cold-drawn copper and certain copper-aluminum alloys to 50 per cent for annealed bronze.

Fracture of Nonmetallic Materials under Creep and under Repeated Stress. Chapter XII on wood contains a little material on the creep

fracture and the fatigue fracture of wood. Chapter XV on concrete gives some results of fatigue tests on concrete. Chapter XVI gives some data on fatigue tests and creep rupture of plastics.

Significance of Results of Tests of Specimens. The values of elastic strength (as shown by yield strength), resistance to creep under long-continued steady load, and of fatigue strength and fatigue limit (endurance limit as given by tests of machines and polished specimens in which there are no notches, holes, grooves, sharp fillets, or other external

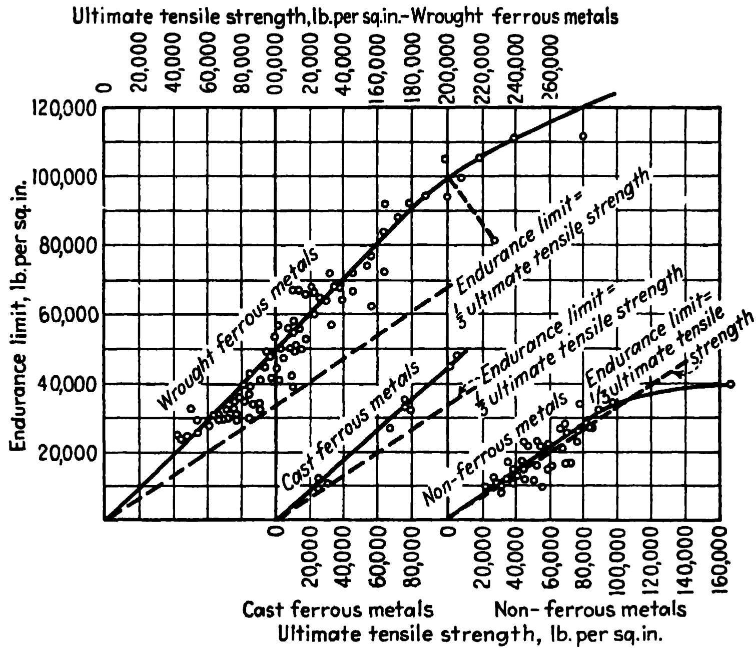


Fig. 40. Correlation diagram; endurance limit and tensile strength.

"stress raisers") show, in general, the highest nominal stresses which the metal can withstand without structural damage. The strength of a structural or machine part made from this metal may show quite different nominal stress limits in service from those shown by the specimen. Under some conditions, the service stresses withstood may be higher than those withstood by the specimen. Some such conditions are heat-treatment, which may be either good for the strength of the part or bad, depending on the precise process used; aging, which increases the strength of some metallic parts; moderate cold-working by rolling, drawing, or shot peening. Under injurious effects may be included: injurious heat-treatment, excessive cold-working, keyways, notches, grooves, sharp fillets, holes, and other "stress raisers," corrosion, wear, increase of size

of part over that of specimen. Besides these evident factors, there are many others. These matters, taken up more fully in Chap. VII, "The Relation of Test Values of Specimens to Design of Structural and Machine Parts," are very important to the designer and user of structural and machine parts.

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Questions

1. What is the difference between the fracture under a single load of a brittle material and of a ductile material?

2. If a brittle material and a ductile material have the same tensile strength, in pounds per square inch, which one will require the greater energy for fracture? Explain.

3. In Fig. 24, do you think that the fracture would have taken place in the same way if the slot and the saw cut had *not* been cut in the specimen? Explain.

4. What is "slip"? Compare the damage done by slip, by creep, and by fracture as to (1) the completeness of failure and (2) detection of failure in its early stages.

5. Are the common "nominal" formulas for stress and strain rigidly correct? Are they *reliable* for use? Explain.

6. In a machine-shop shaft, can the number of cycles of a given range of stress during its period of service be closely predicted? If asked to estimate the number of cycles at a high stress, how would you go about it?

7. What is stress concentration? What is a "stress raiser"? Name some.

8. What is meant by the term "fatigue of metals"? Do you think the term "fatigue" a good one? If not, suggest a better term.

9. Define the following terms used in discussing fatigue tests: stress cycle, maximum stress, range of stress, minimum stress, nominal stress, alternating stress amplitude, mean stress, fatigue life, fatigue limit (endurance limit), stress ratio, *S-N* diagram, cycle ratio, fatigue strength, fatigue ratio (endurance ratio).

10. A certain steel is found to have a fatigue limit under cycles of completely reversed bending stress of 37,500 lb. per sq. in. What is the probable fatigue limit under cycles of stress varying from a maximum in tension to one-quarter as high a stress in compression? What would be the alternating stress component in the two cases?

11. The fatigue limit of the same steel is found to be 22,500 lb. per sq. in. under cycles of completely reversed shearing stress. What would be the probable endurance limit under cycles of shearing stress ranging from zero to maximum?

12. What would be your answers to question 10 if the material were an aluminum alloy with the same fatigue limit under completely reversed stress?

13. What types of fatigue machine have you seen or handled in a series of tests? Which would you choose for fatigue tests of wire? For fatigue tests of round specimens in flexure? For fatigue tests of specimens of sheet metal? What type do you think is the most accurate? Which is the easiest to handle? Which the most adaptable to various types of fatigue tests? Explain in each case.

14. If a machine part is tested under a few thousand cycles of a high stress range, is there any assurance that the part will give satisfactory service under several million cycles of a low stress range?

15. Why is a sharp notch more dangerous in a steel beam subjected to repeated stress than in one subjected to steady load?

16. What is the relation of the endurance limit of a ferrous metal to other physical properties, such as yield strength, tensile strength, elongation at fracture, hardness, etc.?

17. Eight specimens of cold-drawn brass rod were tested under cycles with a stress ratio of -1.0 with the following results:

Stress, lb. per sq. in.	Cycles of stress for fracture
29,600	2,900
26,400	13,100
24,500	37,200
20,900	143,000
17,900	508,000
14,600	1,750,000
13,100	4,800,000
12,500	26,540,000

Draw an *S-N* diagram and determine the fatigue strength for 10,000 cycles of stress, for 100,000 cycles of stress, for 500,000 cycles of stress, for 1,000,000 cycles of stress; also the fatigue limit (endurance limit).

18. In a fatigue test under repeated direct tensile stress, is the tensile stress in the specimen more or less important than the diagonal shearing stress? In a fatigue test in torsion, which is the more important? In a test under repeated direct compression, which is more important?

19. Why is the effect of variation of number of cycles of stress per minute more important in a test of steel at 1200°F. than in a test run at room temperature?

20. Explain the changes found by Gough in the stress-strain diagrams of brass taken after various numbers of cycles of stress (see Fig. 37).

21. Would the lead sheath of an underground power cable, which is subjected to change of bursting stress under changes of current flowing, be more in danger of failure by creep or by fatigue?

22. State structural or machine parts in which the following nonmetals may have to withstand repeated stress: wood, bakelite, rope or cord, ceramics products, concrete, leather, rubber.

CHAPTER VI

TABLES OF PHYSICAL PROPERTIES OF TYPICAL STRUCTURAL METALS

Scope of Chapter. Some tables and graphs of typical physical properties of structural metals have been assembled in this chapter to provide a means for evaluating various properties, including strength, ductility, and toughness. These values are presented for some of the more common structural metals. Obviously, it is impossible to include in an elementary text anything approaching a complete tabulation of the properties of the hundreds of structural metals and alloys now available to the engineer. The references at the end of this chapter list several handbooks which have extensive compilation of such values.

Moreover, new metals and alloys are constantly becoming available, so that it is highly desirable that designing engineers, inspection engineers, and testing engineers not only use the tables of values now listed in handbooks, but that they should follow the current technical publications dealing with materials, such as the *Bulletins* and *Proceedings* of the A.S.T.M., and the magazine, *Metals Progress*, published by the American Society for Metals, to name a few of the many such current technical publications.

Tabulated values of properties, such as these, are generally average values, based on the results of many tests of samples of a given material. Usually these tests have been made by several different investigators on small, polished specimens of a material, frequently with careful attention paid to symmetry of loading and freedom from high internal residual stresses due to bending, stretching, twisting, or compressing. Moreover, the specimen crystal structure is neither homogeneous nor isotropic (with equal resistance to deformation in all directions).

Such test specimens are frequently much smaller in dimensions than are the actual structural machine parts which are to be made of the same material and, if such is the case, a "size effect" may have to be considered. In addition, the actual structural or machine member frequently has irregularities in outline which are not present in the test specimen—rivet holes, screw threads, keyways, fillets with small radius at shaft shoulders, etc., all "stress raisers" which may double or even triple in magnitude the nominal stress set up in a polished, symmetrical, smooth test specimen free from such "stress raisers."

TABLE IV. STRENGTH, DUCTILITY, AND NOTCH TOUGHNESS OF ANNEALED COMMERCIALLY PURE STRUCTURAL METALS

Identification no.	Metal	Weight, lb. per cu. in.	Yield [1] strength, tensile, lb. per sq. in.	Yield [1] strength, shear, lb. per sq. in.	Tensile [2] strength, lb. per sq. in.	Endurance limit under reversed bending, lb. per sq. in. Millions of cycles of stress to fracture					Brinell hardness no.	Charpy [3] notched bar impact, ft.-lb.	Elongation in 2 in. after fracture, per cent
						0.1	1.0	10	100	Indef. large			
1	Iron	0.283	19,000	13,600	42,000	32,000	26,000	26,000	26,000	26,000	69	50	48
2	Wrought iron	0.280	30,000	18,000	50,000	38 000	30,000	23,000	22,000	22,000	100	17	35
3	Copper	0.322	5,000	......	32,000	19,000	14,000	11,500	10,500	[4]	47	30	56
4	Nickel	0.321	18,000	......	69,000	40,000	35,000	30,500	28,000	28,000	90	72	45
5	Aluminum	0.097	6,000	4,000	16,000	13,200	9,400	7,800	7 000	7,000	28	19	40
6	Magnesium	0.063	8,500	5,000	25,000	11,500	8,700	8,000	8,000	8,000	33	3	6
7	Lead [5]	0.675											
8	Tin [5]	0.262											
9	Zinc [5]	0.258											
10	Tungsten [6]	0.675	....	......	220,000								

[1] Yield strength determined by the stress corresponding to an "offset" of 0.2 per cent from the straight-line part of the stress-strain diagram. Yield strength in compression may be taken as approximately equal to yield strength in tension.

[2] Ultimate strength in compression may be taken as equal to yield strength in compression for practical purposes.

[3] Probably these Charpy values are rather high, except for magnesium.

[4] The *S-N* diagram for copper had not become horizontal at 100,000,000 cycles of stress.

[5] Lead, tin, and zinc creep at ordinary room temperature, and their strength, ductility, and toughness depend on the rate of application of load and the time under load.

[6] Specimens of tungsten were in the form of drawn wire, 0.025 in. in diameter.

It is rarely possible to use the test results given by laboratory tests of small specimens without some modification of the nominal stress values to allow for those unavoidable physical differences between the test specimens and the actual structural or machine part. If tests of full-size members can be made, such test results need less modification than do test results from small specimens. However, this use of full-size specimens is rarely practicable, so that "factors of safety" must be used in designing actual structural or machine parts.[1] Putting this matter in another way, we may consider the tabulated results of tests of specimens of metals to be an index of the *maximum* loads and moments which can be withstood. The limit of successful resistance to service stresses will then be allowable (or working) stresses *less than* the test values for specimens, and frequently much less.

Notes on the Use of the Tables. For structural and machine parts subjected to static loading at ordinary room temperature,[2] the values of yield strength given by tests of specimens in tension, compression, or shear may generally be used as a basis for design, the yield strength being divided by a factor of safety to allow for uncertainties in the loads and moments which the part must withstand in service.

In the case of parts under high temperature, continuing "creep" of the metal occurs, and the ratio of creep rate to length of service without fracture or undue distortion must be considered. Then, too, under creep many metals tend to become brittle. This may be accounted for by the cracks which appear after a long time under steady load and which tend to spread.

In the case of parts under repeated stress, "stress raisers," surface conditions, residual stresses, and size effects on the strength of the piece, are factors which must be considered, and the limiting stress for a given number of cycles of stress does not bear any close relation to yield strength, and a "fatigue strength" must be determined by test. Whenever feasible, full-size tests are desirable, but unfortunately this is rarely the case and tests of specimens with allowances for stress raisers, residual stresses, etc., furnish the best guides now available.

The figures for elongation after fracture, which are a conventional measure of ductility, will not enter directly into design computations.

[1] It may be noted that a factor of safety (better termed a factor of uncertainty) is also necessary in estimating the actual loads and moments to which a part will be subjected, their probable number, their frequency, and whether the part may be given a period of being "broken in" under relatively light loads before it is subjected to the heavier loads and moments of severe service.

[2] The strength of lead, tin, or zinc is materially affected by changes in room temperature.

TABLE V(A). CHEMICAL COMPOSITION, TREATMENT DURING MANUFACTURE, AND SUBSEQUENT HEAT-TREATMENT OF TYPICAL STEELS

Identification no.	Steel	Alloying elements, per cent [1]						Treatment during manufacture	Subsequent heat treatment
		Carbon	Manganese	Silicon	Nickel	Chromium	Molybdenum		
F101	Common structural steel	0.18	0.37	0.06	....	.....	....	Hot-rolled	None
F102	Medium-carbon steel	0.49	0.46	0.12	....	.....	....	Hot-rolled	Water-quenched,[2] drawn at 1050°F.
F103	Rail steel	0.75	0.80	0.15	....	.....	....	Hot-rolled and control-cooled	None
F104	Spring steel	0.93	0.38	0.02	....	.....	....	Hot-rolled	Oil-quenched, drawn at 850°F.
F105	Low-alloy steel	0.08	0.37	0.07	0.69	.....	0.07	Hot-rolled	None
F106	Chrome-nickel steel	0.24	0.37	0.15	3.35	0.87	....	Hot-rolled	Oil-quenched, drawn at 700°F.
F107	Chrome-nickel steel	0.24	0.37	0.15	3.35	0.87	0.07	Hot-rolled	Oil-quenched, drawn at 1200°F.
F108	Nickel steel	0.41	0.75	0.25	3.41	0.18	....	Hot-rolled	Oil-quenched, drawn at 1200°F.
F109	Chrome-molybdenum steel	0.31	0.55	....	....	1.08	0.20	Hot-rolled	Heat-treated to 300 Brinell hardness
F110	Stainless steel	0.12	0.47	0.58	9.67	18.50	.	Hot-rolled	Water-quenched from 2000°F., not drawn
F111	Steel casting, treatment A	0.25	0.68	0.32	....	.....	....	Cast in mold	None
F112	Steel casting, treatment B	0.25	0.68	0.32	....	.....	....	Cast in mold	Normalized at 1650°F., reheat to 1525°F., cool in air

[1] Sulphur and phosphorus less than 0.05 per cent in all cases.
[2] Not quite the composition given for that A.I.S.I. number, but the number given is the nearest to the actual composition of the steel tested.

TABLE V(B). STRENGTH, DUCTILITY, AND NOTCH TOUGHNESS OF TYPICAL STEELS

The steels listed in this table are the same as those listed in Table V(A). The values listed in this table are values at ordinary room temperature

Identification no.	Steel	Yield strength, tensile, lb. per sq. in.	Yield strength, shear, lb. per sq. in.	Tensile strength, lb. per sq. in.	Endurance limit under reversed bending, lb. per sq. in. — Millions of cycles of stress to fracture: 0.1	1	10	100	Indef. large	Brinell hardness no.	Charpy notched bar impact, ft.-lb.	Elongation in 2 in. after fracture, per cent
F101	Common structural steel	40.000	24,000	61,000	40,000	33,000	28,500	28.500	28,500	120	32	41
F102	Medium-carbon steel	69,700	40,000	96,900	56,000	45.000	41,000	41,000	41,000	197	22	24
F103	Rail steel	73,000	43.000	137,000	78,000	66,000	66.000	66.000	66,000	272	3	8
F104	Spring steel	120,000	76.000	188.000	103.000	98,000	98,000	98.000	98.000	380	4	10
F105	Low-alloy steel	49,000	30,000	66,500	55,000	47,000	45,000	45,000	45,000	135	...	32
F106	Chrome-nickel steel, oil quench drawn at 700°F.	128,000	84.900	138,700	87,000	69,000	68,000	68,000	68,000	291	41	18
F107	Chrome-nickel steel, oil quench drawn at 1200°F.	103.700	64,000	113.300	80,000	66.000	65.000	65,000	65,000	247	54	24
F108	Nickel steel	91,100	55.000	111.800	75,000	63.000	62.000	62,000	62.000	242	41	24
F109	Chrome-molybdenum steel	115,000	69,000	141,800	90.000	72,000	69,000	68,000	68,000	300	...	17
F110	Stainless steel	41.000	......	91,000	47,000	40.000	40,000	40,000	40,000	153	107[1]	62
F111	Steel casting, treatment A	26,700	......	67,200	39,000	33.000	28,000	27.000	27,000	119	20	22
F112	Steel casting, treatment B	43,600	......	76,600	42,000	40,000	37,000	35,000	35,000	136	33	30

[1] Izod notched-bar test result, data on Charpy test lacking.

TABLE VI(A). CHEMICAL COMPOSITION OF TYPICAL GRAY CAST IRONS, MALLEABLE CAST IRON, AND NODULAR CAST IRON

Iron	Chemical content, per cent										
	Total carbon	Combined carbon	Graphitic carbon	Manganese	Silicon	Nickel	Chromium	Molybdenum	Copper	Sulfur	Phosphorus
Common gray cast iron	3.25	0.80	2.45	0.80	2.74	....	...	...	....	0.12	0.15
Alloy gray cast iron	3.04	0.90	2.14	1.05	1.99	0.12	0.22	0.54	0.92	0.10	0.12
Malleable cast iron	2.00	. .	.	0.35	0.95	....	....	....	...	0.12	0.15
Nodular cast iron[1]	3.48	...	...	0.51	2.15	1.78	....	....	....	0.008	0.12

[1] The nodular cast iron contained 0.08 per cent magnesium.

TABLE VI(B). STRENGTH OF TYPICAL GRAY CAST IRONS, MALLEABLE CAST IRON, AND NODULAR CAST IRON

Iron	Yield strength tensile, lb. per sq. in.	Tensile strength, lb. per sq. in.	Millions of cycles of stress to fracture: 0.01	0.10	1.00	10	Indef. large	Brinell hardness no.	Elongation in 2 in., per cent
			Endurance limit under reversed bending, lb. per sq. in.						
Common gray cast iron	... [1]	21,000	14,500	11,800	10,500	9,300	9,300	190	Very small[2]
Alloy gray cast iron	..... [1]	51,000	34,000	28,500	23,500	21,000	21,000	238	Very small[2]
Malleable cast iron	32,000	50,000	48,000	38,500	29,000	25,000	25,000	110	10
Nodular cast iron	51,200	71,500	.....	......	......	......	24,000	170	8

[1] No significant yield strength for gray cast iron.
[2] Elongation less than 5 per cent.

TABLE VII(A). CHEMICAL COMPOSITION OF TYPICAL NONFERROUS STRUCTURAL METALS

Identification no.	Metal	Chemical composition, per cent
NF1	Brass, cold-drawn rod	Copper, 62; zinc, 35; lead, 3.0
NF2	Bronze, cast metal	Copper, 90; tin, 10
NF3	Aluminum bronze, extruded rod	Copper, 90; aluminum, 9.9; iron, 0.1
NF4	Manganese bronze, chill-cast	Copper, 96; manganese, 2.0; silicon, 1.5; iron, 0.5
NF5	Phosphor bronze, cold-rolled sheet	Copper, 91; tin, 8.1; small amounts of iron, lead, and phosphorus
NF6	Monel metal, hot-rolled bar	Copper, 27.3; manganese, 1.38; nickel, 69.0; iron, 2.32
NF7	Duralumin, extruded rod	Copper, 4.5; manganese, 0.6; magnesium, 1.5; aluminum, remainder
NF8	Aluminum-copper alloy, cast metal	Copper, 8; silicon 1.2; aluminum, remainder
NF9	Aluminum-zinc alloy, hot-rolled bar	Copper, 1.6; zinc, 5.6; magnesium, 2.5; manganese, 0.2; chromium, 0.33; aluminum, remainder
NF10	Magnesium-aluminum alloy, annealed sheet	Zinc, 0.7; aluminum, 6.5; magnesium, remainder
NF11	Magnesium-aluminum alloy, cast metal	Aluminum, 10.0; manganese, 0.1; magnesium, remainder
NF12	Magnesium-aluminum alloy, extruded rod	Aluminum, 4.0; manganese, 0.3; magnesium, remainder
NF13	Copper-beryllium alloy, rolled rod or strip, heat-treated	Beryllium, 2.0; manganese, 0.35; copper, remainder
NF14	Die-casting alloy, aluminum base	Copper, 7.0; silicon, 2.0; aluminum, remainder
NF15	Die-casting alloy, magnesium base	Aluminum, 8.0; manganese, 0.15; magnesium, remainder
NF16	Die-casting alloy, zinc base	Aluminum, 3.9; magnesium, 0.05; zinc, remainder
NF17	Inconel, annealed	Nickel, 79.5; chromium, 13.0; iron, 6.5; small amounts of carbon, manganese, and sulphur

TABLE VII(B). STRENGTH, NOTCH TOUGHNESS, AND DUCTILITY OF TYPICAL NONFERROUS STRUCTURAL METALS

The chemical composition and the properties of the metals listed in this table are the same as those of the metals listed with the same identification numbers in Table VII(A). Values are for properties at room temperature

Identification no.	Metal	Yield strength,[1] tensile, lb. per sq. in.	Yield strength, shear, lb. per sq. in.	Tensile strength, lb. per sq. in.	Endurance limit for reversed bending, lb. per sq. in. Millions of cycles of stress for fracture: 0.1	1.0	10	100	Indef. large	Brinell hardness no.	Charpy notched bar impact, ft.-lb.	Elongation in 2 in., per cent
NF1	Brass, cold-drawn rod	42,000	22,000	48,700	28,000	22,500	16,000	14,000	13,000	124	..	23
NF2	Bronze, cast metal	21,000	.....	47,000	......	......	......	......	......	62	..	12
NF3	Aluminum bronze, extruded rod	28,000	.....	77,500	......	......	......	27,000	[1]	142	13	20
NF4	Manganese bronze, chill cast	14,800	....	32,300	......	......	......	21,000	[1]	70	..	17
NF5	Phosphor bronze, cold-rolled sheet	57,000	......	60,000	39,000	24,500	21,000	21,000	21,000	156	..	5
NF6	Monel metal, hot-rolled bar	57,000	......	90,200	51,000	47,500	44,000	41,000	[1]	163	74	36
NF7	Duralumin, extruded rod	44,000	......	68,000	31,000	27,600	22,500	18,500	[1]	105	..	22
NF8	Aluminum-copper alloy, cast metal	14,000	......	21,000	..	...	...	8,000	[1]	60	2	2
NF9	Aluminum-zinc alloy, hot-rolled bar	76,000	44,700	86,300	45,000	37,000	32,000	27,000	[1]	175	..	9
NF10	Magnesium-aluminum alloy, annealed sheet	24,200	......	42,500	14,500	11,600	11,600	11,600	11,600	...	..	20
NF11	Magnesium-aluminum alloy, cast metal	13,000	......	22,000	......	.....	......	9,000	[1]	54	1	2
NF12	Magnesium-aluminum alloy, extruded rod	29,000	....	40,000	.....	......	......	14,500	[1]	47	..	16
NF13	Copper-beryllium alloy, rolled rod or strip, heat-treated	119,400	......	200,900	......	58,000	51,000	45,000	[1]	400	..	3
NF14	Die-casting alloy, aluminum base	24,000	....	30,000	......	......	......	17,000	[1]	80	2	10
NF15	Die-casting alloy, magnesium base	17,000	......	30,000	......	......	......	......	.....	53	2	3
NF16	Die-casting alloy, zinc base	[2]	......	....	......	......	......	......	.....	...	20	5[2]
NF17	Inconel, annealed	28,000	...	86,000	......	......	......	32,500	[1]	125	..	50

[1] Either available data show that S-N diagram had not become horizontal at 100,000,000 cycles of stress, or data for endurance limit for smaller number of cycles of stress were not available.

[2] Zinc "creeps" at room temperature, hence strength values depend on rate of loading and on time under load. Values for Charpy notched-bar tests and for elongation are for short time tests.

Those values represent acceptability of the metal rather than any quantitative value to be used in design. For example, if medium-carbon steel [Table V(B)] has an elongation much less than 24 per cent, it is an index that it is not very good steel, but it is no indication that spring steel should be expected to have so large an elongation or that an aluminum-zinc alloy [Table VII(B)] should be rejected because it had a much lower elongation.

Under *static compressive* loads the yield strengths of the common structural metals may, in general, be safely taken as equal to the yield

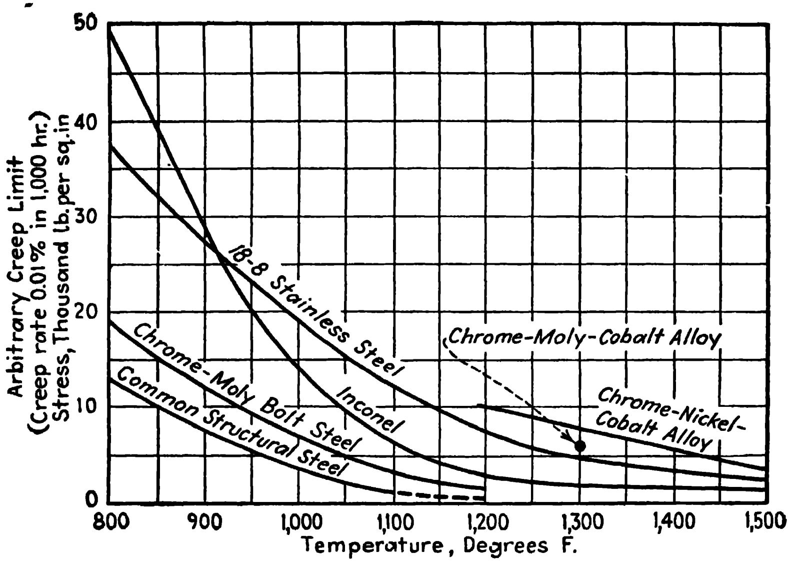


FIG. 41. Creep-limit diagrams for several structural steels.

strength in tension, and the yield strength under shearing stress (*e.g.*, the stresses in a shaft in torsion) may be taken as 55 per cent of the yield strength in tension, as a general rule. In some cases it will be noted that test values of yield strength in shear are given, and in the references at the end of this chapter many other values of yield strength in shear and in compression are given.

The values of tensile strength are rather rarely of direct use in design. When working stress is determined by dividing tensile strength by the so-called "factor of safety," the factor usually includes the ratio of yield strength to tensile strength, which for soft and medium structural steel is rarely less than ½ and is commonly about 60 per cent. For the stronger steels and for the nonferrous metals it is better to work from the yield strength when determining static resistance to structural damage. Brittle metals, especially cast iron, have no well-defined yield strength;

for static loads the tensile strength seems the most suitable basis. Some brittle metals usually have a definite compressive strength and in Table VIII some values are given. For ductile metals the yield strength may be regarded as the practical ultimate strength, since disastrous buckling is liable to occur at higher stresses.

In machine or structural parts made of ductile metal, the effect of stress concentration (see Chap. VII, page 123) is usually small under *static* loads, but is very important under *repeated* loads. For brittle metals,

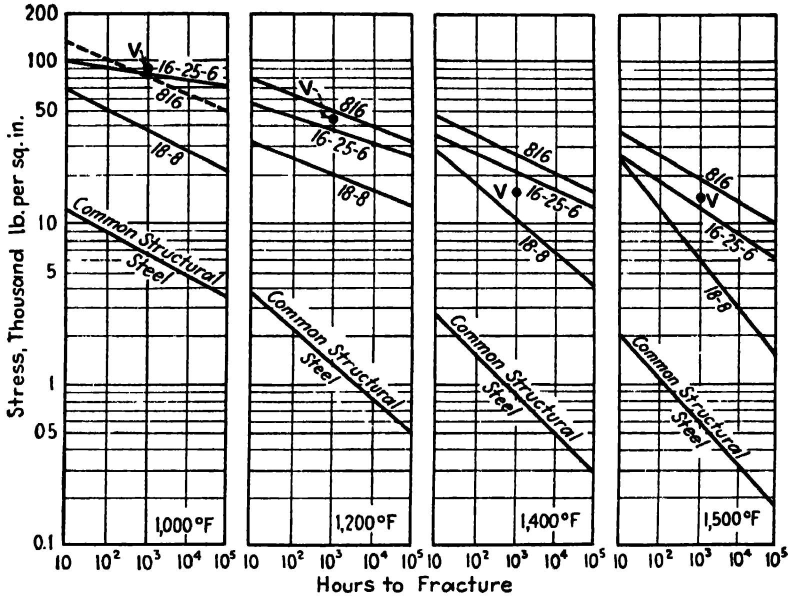


FIG. 42. Strength-time diagrams of several structural steels under long-continued, steady tensile load at different temperatures. For composition of steels see corresponding identifying marks in Table X(A), page 87. These graphs are evidently based on the "straight-line" diagram shown in Fig. 22. For the sake of safety the stress values might well be reduced by 25 per cent for 10^4 hr. to fracture and by 50 per cent for 10^5 hr. to fracture. Stress values up to 10^3 hr. to fracture are shown in the diagrams.

especially for gray cast iron, under *static* loads the effect of stress concentration is very marked, and computation should be made of the probably stress concentration at holes, notches, grooves, keyways, fillets, and other "stress raisers." The dividing line between ductile and brittle metals under static load is by no means fixed, but metals with less than 5 per cent elongation in 2 in. may, it seems to the writer, be regarded as brittle. *Under repeated loads, stress concentration should always be considered.*

For parts to be subjected to elevated temperatures, the graph of creep

limits (Fig. 41), the short-time strength at elevated temperatures [Table X(B)], and the graph of fracture strength under long-continued steady loads (Fig. 42) may be used. Under long-time tests at high temperatures the ductility of metal is seriously diminished. A typical example of this is shown in Fig. 22, page 40 for plain carbon steel. The mechanism of creep and fracture of metals under elevated temperature has been discussed in Chap. IV, and the loss of ductility under continued creep is explained.

Creep and fracture under continued creep of steels and special alloy steels are of the most importance to engineers, but similar phenomena are

TABLE VIII. ULTIMATE COMPRESSIVE STRENGTH OF SOME STRUCTURAL METALS
Most rolled or drawn structural metals do not have any clearly defined ultimate compressive strength. Many of the cast metals and a few rolled or drawn metals with low ductility do have a definite compressive strength, with a diagonal fracture, probably due mainly to shearing stress. The value obtained by dividing the maximum load during a compression test of a short specimen by the original area of cross section is called the ultimate compressive strength or, sometimes, simply the compressive strength. In this table are listed values of compressive strength for some of the typical structural metals listed which have a definite compressive strength.

Identification no.	Metal	Compressive strength, lb. per sq. in.
6	Magnesium	34,000
F113	Common gray cast iron	80,000
F114	Alloy gray cast iron	136,000
NF11	Magnesium-aluminum alloy, cast metal	48,000
NF12	Magnesium-aluminum alloy, extruded rod	59,000
NF9	Aluminum-zinc alloy, hot-rolled	124,900
NF8	Aluminum-copper alloy, cast metal	64,000

shown by nonferrous metals at considerably lower temperatures than the minimum temperature, about 700°F., under which creep becomes important as a factor affecting the strength of iron and steel parts.[1] Much information concerning properties of metals, including the nonferrous, may be found in references at the end of this chapter.

Creep and fracture under continued creep are of importance in the very soft metals, even at temperatures as low as 32°F. An illustration

[1] For machine parts in which even a slight distortion affects the accuracy of the machine, creep at lower temperatures may be important, *e.g.*, in springs for measuring load and parts of precision machine tools. Hence the importance of "aging" such parts before they are put in service.

of this is found in the distortion and fracture occasionally found in the lead sheathing of underground and aerial electric cables after some years of service.

Figure 43 shows graphs of creep and fracture of a typical lead alloy for cable sheathing. Short-time strength under high temperature is of importance as a measure of a metal part to withstand occasional loads in service, loads lasting but a short time and not repeated more than a few times.

Under very low temperatures, metals, in general, show increased strength but distinctly decreased ductility and toughness. In extreme

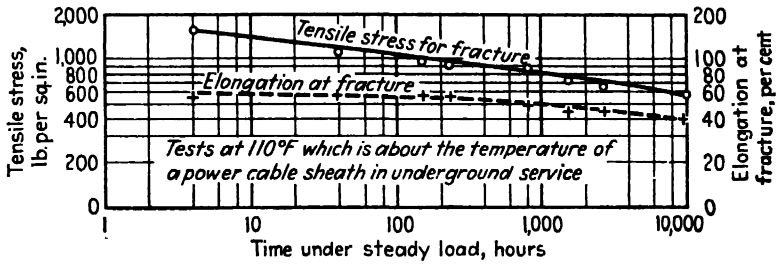


FIG. 43. Strength-time diagrams and elongation-time diagrams for cable-sheathing lead. This particular metal contained 99.93 per cent lead and 0.06 per cent copper. (*Courtesy of C. W. Dollins, University of Illinois.*)

cases, steel plates under temperatures no lower than 32°F. have fractured, like a brittle material, by sudden "cleavage." Under decreasing temperatures, rail steel under impact load shows decreasing toughness and, at a critical temperature somewhat below freezing, the toughness decreases very rapidly. Steels of very nearly the same chemical composition vary markedly in low temperature toughness. The tendency to develop a brittle-cleavage failure under a single load rather than the conventional necking down to fracture is increased by the presence of "stress raisers." This is under study in a number of laboratories at the present time.

The matter of the tabulated figures for strength under repeated loads (fatigue strength for various numbers of cycles of stress) is decidedly more complicated than the use of the figures for static strength. The values given in Tables IV, V(B), VI(B), and VII(B) are results of reversed bending tests of polished specimens about ¼ in. in diameter and free from "stress raisers." Undoubtedly the ideal way to determine fatigue strength of a machine or structural part is to make tests of full-size finished parts under actual service conditions, or under combinations of stresses such as the part may be expected to withstand in service. This testing procedure can be carried out in the case of small parts

TABLE IX. ELASTIC STIFFNESS OF TYPICAL STRUCTURAL METALS

Identification no.	Metal	Modulus of elasticity, lb. per sq. in.	
		Tension	Shear
1	Commercial pure iron	29,000,000	11,600,000
2	Wrought iron	27,000,000	11,000,000
F101–F112	All steels	30,000,000	12,000,000
F113	Common gray cast iron	11,900,000	5,000,000
F114	Alloy gray cast iron	22,700,000	9,600,000
F115	Malleable cast iron	25,000,000	10,000,000
3	Copper	17,500,000	7,000,000
4	Nickel	30,000,000	11,000,000
5	Aluminum	9,600,000	3,840,000
6	Magnesium	6,400,000	2,500,000
7	Lead	[1]	[1]
8	Tin	[1]	[1]
9	Zinc	[1]	[1]
10	Tungsten	50,000,000	20,000,000
NF1	Cold-drawn brass	13,000,000	5,200,000
NF2	Bronze, cast metal	12,600,000	5,000,000
NF3	Aluminum bronze, extruded rod	20,000,000	6,500,000
NF4	Manganese bronze, chill cast	14,100,000	5,600,000
NF5	Phosphor bronze, cold-rolled sheet	16,200,000	6,480,000
NF6	Monel metal, hot-rolled bar	25,000,000	9,600,000
NF7	Duralumin, extruded rod	10,500,000	4,000,000
NF9	Aluminum-zinc alloy, hot-rolled bar	10,300,000	3,900,000
NF10	Magnesium-aluminum alloy, annealed sheet	6,200,000	2,400,000
NF11	Magnesium-aluminum alloy, cast metal	6,500,000	2,500,000
NF12	Magnesium-aluminum alloy, extruded rod	6,100,000	2,350,000
NF13	Copper-beryllium alloy	19,600,000	7,840,000
NF14	Die-casting alloy, aluminum base	10,300,000	4,120,000
NF15	Die-casting alloy, magnesium base	6,500,000	2,600,000
NF16	Die-casting alloy, zinc base	[1]	[1]

[1] Zinc, lead, and tin "creep" at ordinary room temperatures. This makes the determination of their moduli of elasticity a very uncertain matter, depending on the rate of application of load.

made in large number, *e.g.*, automobile drive shafts, ball and roller bearings and springs. However, such a procedure involves very large numbers of tests and the destruction of large numbers of small parts; it cannot well be used for getting data on which to base the design of large parts of heavy machinery, or the preliminary choice of metal for study and test.

In using the figures for endurance limit given in the tables, the values should be considered as representing the fatigue strength under reversed

TABLE X(A). CHEMICAL COMPOSITION OF TYPICAL HEAT-RESISTANT STRUCTURAL METALS AND OF A TYPICAL STRUCTURAL STEEL

Identification mark	Metal	Chemical composition, per cent
816	Chromium-nickel-cobalt alloy	Carbon, 0.40; silicon, 0.40; manganese, 0.50; chromium, 20.0; nickel, 20.0; cobalt, 43.0; molybdenum, 4.0; tungsten, 4.0; columbium, 4.0; iron, 4.0
V	Chromium-molybdenum-cobalt alloy	Chromium, 28.0; molybdenum, 6.0; nickel, 2.0; carbon, 0.25; remainder, cobalt
16-25-6	Chromium-nickel-molybdenum alloy	Chromium, 16.0; nickel, 25; molybdenum, 6.0; small amounts of nitrogen, manganese, and silicon; remainder, iron
18-8	Stainless steel	Carbon, 0.12; manganese, 0.47; silicon, 0.58; nickel, 9.7; chromium, 18.5; remainder, iron
	Carbon-molybdenum bolt steel	Carbon, 0.16; manganese, 0.48; silicon, 0.25; molybdenum, 0.50
Inconel	Nickel-chromium alloy	Nickel, 79; copper, 0.30; chromium, 13.5; iron, 6.8
F101	Structural steel	Carbon, 0.18; manganese, 0.37; silicon, 0.06

bending under the most favorable conditions. Using the figures from the tables as a basic value, the following factors must be considered: (1) range of stress, (2) size of the machine or structural part, (3) stress concentrations at holes, notches, fillets, screw threads, keyways, or other "stress raisers," (4) residual stresses in the metal, (5) surface conditions of the metal, (6) temperature to be withstood in service, and (7) corrosion in service.

The effect of range of stress is discussed in Chap. V, page 62, and the formulas given there are believed to be conservative.

The endurance limit will probably be smaller for the part than for the specimen values in the table unless the thickness or diameter of the part is ¼ in. or less.

The test data on fatigue strength of metals under elevated temperature are very few, and none are given in the tables in this chapter. The reason for this is that under temperatures high enough to affect the fatigue strength appreciably, creep occurs; if fracture takes place, it is due to a

TABLE X(B). SHORT-TIME TENSILE TEST RESULTS FOR TYPICAL HEAT-RESISTING STEELS AND FOR A TYPICAL STRUCTURAL STEEL

Ordinary testing machine tests. Results may be compared with the results of long-time tests to fracture under a steady load, shown in Fig. 42

Identi-fication mark	Metal	Tensile strength, lb. per sq. in.				Elongation in 2 in. after fracture, per cent			
		Room temp.	1000° F.	1200° F.	1500° F.	Room temp.	1000° F.	1200° F.	1500° F.
816	Chromium-nickel-cobalt alloy	159,000	150,000	120,000	78,200	21	20	17	13
V	Chromium-molybdenum-cobalt alloy	105,000	....	. .	59,000	.	.	. .	7
16-25-5	Chromium-nickel-molybdenum alloy	109,000	. . .	67,000	43,000	49	. .	20	40
18-8	Stainless steel	91,000	61,600	44,400	17,200	62	44	48	54
F101	Structural steel	61,000	30,500	16,300	7,000	41	53	71	80

combination of creep and repeated stress. Evidently the longer the time between successive cycles of repeated stress, the more will creep reduce the resistance to fracture, so that, although for repeated stress without appreciable creep the number of cycles per minute has very little effect within the limits of ordinary tests, under combined repeated stress and creep the greater the frequency of cycles of stress the higher will be the fatigue strength *for a given number of cycles of stress.* If, however, the length of service of the part is regarded limited by the *hours* necessary to produce creep fracture, then the greater the frequency of cycles of stress the *greater* will be the reduction of time necessary for fracture below the *time* required for fracture under creep without repeated stress added.

In the absence of definite data, the writers suggest that, for temperatures of 1400°F. and over, the strength of the steels and the special heat-resisting alloys be regarded as the fracture strength under *creep.* For combined repeated stress and creep, it is suggested that the strength be regarded as a fatigue strength varying from fatigue strength at room

temperature to the creep strength at 1400°F., or the creep strength at the temperature of the part in service, if that temperature is above 1400°F. Readers of this book should regard this as a temporary expedient to be abandoned as soon as a better basis is found for the determination of fracture stress under simultaneous creep and repeated stress.

The strength of metals subjected to simultaneous repeated stress and corrosion is discussed in Chap. VIII. No clearly defined endurance limit has been found for metals subjected to simultaneous repeated stress and corrosion. At the present time, the best defense against corrosion under stress seems to be the use of protective coatings which can be renewed from time to time.

Selected References for Further Study

1. EVERHART, LINDLIEF, KANEGIS, WEISSLER, and SIEGEL: "Mechanical Properties of Metals and Alloys," *Nat. Bur. Standards Circ.* C447, Washington, D. C., 1943.
2. HOYT, S. L.: "Metals and Alloys Data Book," Reinhold Publishing Corporation, New York, 1943.
3. "The Metals Handbook," 1948 ed., American Society for Metals, Cleveland, Ohio.

The following periodicals contain many articles giving information on current developments in metals and alloys:

4. *Metals Progress*, published monthly by the American Society for Metals, Cleveland.
5. *Transactions, Am. Soc. Metals*, published semiannually by the Society.
6. *Bulletin of the A.S.T.M.*, published monthly by the Society, Philadelphia, Pa.
7. *Proceedings of the A.S.T.M.*, published annually by the Society.
8. *Materials and Methods*, published monthly by the Reinhold Publishing Corporation, New York.
9. *The Iron Age*, published weekly by the Chilton Co., New York.
10. EAGAN, T. E., and J. D. JAMES: "A Practical Evaluation of Ductile Cast Iron," *Iron Age*, Dec. 15, 1949.

Questions

1. Distinguish between ductility and toughness of a metal. In what units is each measured?

2. It is stated in this book that the results of tests of small specimens cannot be used without modification in assigning working stresses to a large structural or machine part, *e.g.*, a steel column, or the drive shaft of a large gas engine. Do you agree with this statement? Give reasons for your answer.

3. Why is the yield strength a satisfactory basis for design of structures subjected to only a few loads, and *not* a very good basis for design of structures or parts subjected to oft-repeated load?

4. Is the yield strength a more important value for parts under tension than for parts under compression? Explain.

5. What are "stress raisers"? When are they of great importance under steady load on a structure or machine? When are they of importance under repeated load on a machine or structure? Give your estimate of how much a screw thread may

reduce the strength of a steel bolt, under steady load, under repeated load. How about a bolt made of gray cast iron?

6. It is quite generally recognized that stress raisers do less proportionate damage to a part made of relatively weak ductile metal than they do to a similar part made of a high-strength metal with low ductility. Explain this.

7. What is creep? Name two structural or machine members in which creep strength is an important property. Is there known to be a limiting stress below which creep will not occur at all? That is, is there a real "creep limit"?

8. What is meant by the term "fatigue of metals"? Is the term "fatigue" well chosen? Give your reasons.

9. Define "endurance limit," "fatigue strength," *S-N* diagram.

10. Explain why there is a difference between a "theoretical" stress-concentration factor and the fatigue-strength reduction factor found in actual tests.

11. Why is a sharp notch more dangerous in a steel shaft subjected to repeated loading than to a similar shaft subjected to steady loading?

12. Define "cycle of stress."

13. What evidence is there for the existence of an endurance limit, measured in pounds per square inch, below which the part will not fail under an indefinitely large number of cycles of stress?

14. By some writers the endurance limit is defined as that stress range within which the metal will withstand an *infinite* number of cycles of stress. Do you prefer "infinite" or "indefinitely large"? State your reasons.

15. Eight specimens of steel were tested under cycles of reversed bending stress, with the following results:

'ess (maximum), lb. per sq. in.	Cycles of stress for fracture
95,000	25,200
86,000	56,100
77,900	101,200
70,100	165,100
61,400	550,200
58,000	4,100,000 (did not break)
60,000	15,000,000 (did not break)

What is the endurance limit, the fatigue strength for 30,000 cycles of stress, for 100,000 cycles, for 1,000,000 cycles?

16. Using the same steel as that mentioned in question 15, specimens were tested under cycles of stress ranging from zero to a maximum in tension. What would you expect the endurance limit to be?

CHAPTER VII

STRUCTURAL DAMAGE; WORKING STRESS; FACTOR OF SAFETY

Structural Damage. When a machine or a structure ceases to function properly on account of excessive deformation, yielding, cracking, or fracture, "structural damage" may said to have taken place. It is generally assumed that such structural damage is caused by excessive *stress* set up in the damaged parts by loads or moments applied to the structure or machine.

Today there are four theories of the cause of structural damage: (1) the maximum-stress theory, which holds that stress, tensile, compressive, or shearing, is the cause of structural damage; (2) the maximum-strain theory, which holds strain to be the cause; (3) the total-strain-energy theory, which holds that the combined energy of all the combined stresses in the damaged region is the cause of structural damage; and (4) the distortion-energy theory, which holds, in effect, that the energy of the shearing strain-stress pattern in the damaged region is the cause of structural damage. Test results indicate that for ductile material the distortion-energy theory seems to fit the results best, while for brittle materials the results fall between the values for the maximum-stress and those for the maximum-strain theory.

Practically, the difference between the results indicated by the different theories is not very great, especially if the shearing stresses are always carefully considered, and the commonly used stress theory can be employed to measure the tendency to cause structural damage.

Working Stress. In the study of mechanics of materials *stress* is considered as the intensity of an internal force in a body which resists external forces acting on the body. In dealing with members of structures and machines it is needful to hold this in view, and to consider also the destructive effect of stress, and the accompanying strain, on the materials used. Two questions must be answered: (1) What is the maximum stress set up in the body? This is a question to be answered by mathematical analysis, by an experimental study of strains under service conditions, or by a study of successes and failures of structural or machine parts in service.[1] (2) Does this stress exceed the safe stress for the

[1] For an illustration of a combination of these three methods see "First Progress Report of Special Committee on Stresses in Railroad Track," *Proc. Am. Ry. Eng. Assn.*, Vol. 19, 1918; also *Trans. Am. Soc. Civ. Engr.*, Vol. 82, 1918. Also "Seventh

material used? This question depends for its answer a knowledge of the strength properties of materials.

In considering the safety under load of a structure or a machine, several points of view are possible. The designer wishes to know how large the members must be to carry the given load; the purchaser wishes to know how great a load can be safely carried by the machine or the structure; the inspector wishes to know how large are the stresses set up by the loads actually imposed on the structure or the machine. All these points of view involve a consideration of the stress set up by the working load, that is, of the working stress. A *safe working stress* for the material in a structure or a machine may be defined as a stress (measured in pounds per square inch) which under the conditions of operation or use will not cause structural damage.

The maximum safe working stress for any material is always less, much less, than the extreme strength (see page 7) of the material (as determined by tests of sample test specimens). Four general reasons may be given for this fact:

1. A structure or machine would not give satisfactory service if it were on the point of failure. Nearly all materials show marked distortion before failure, and the stiffness is greatly reduced.

2. Complete information as to the properties of the material in any actual machine or structure is never available. Sometimes the process of manufacture of the material is not known (for example, it may not be known whether steel is bessemer steel or open-hearth steel; whether concrete is hand-mixed or machine-mixed). The thoroughness of testing and of inspection of material varies widely for different classes of work. If the material is a part of a large shipment, the inspection and testing may have been very thorough; if the shipment was a small one, there may have been no inspection at all. The process of fabrication of the material may have weakened it, as in the case with steel plates or shapes in which holes have been punched for rivets, or which have been bent or hammered into position without being heated. The material may suffer deterioration as time elapses. For example, steel exposed to moist air or to smoke corrodes unless kept thoroughly covered with a coat of paint; concrete may be weakened by electrolysis from stray currents from nearby electric circuits; wood decays.

3. The magnitude of the loads actually applied to a machine or a structure, and the magnitude of the stresses set up are never known exactly. The loading actually placed on the floor of a building or on the

Progress Report of the Joint Investigation of Fissures in Railroad Rails," *Bull.* 423, *Am. Ry. Eng. Assn.*, 1941, also *Reprint Series, Univ. Ill. Eng. Expt. Sta. Bull.* 21.

roadway of a bridge, or the actual working load on a machine will not, in general, be exactly that assumed in the design. The fitting of members to each other is never perfectly done, and the distribution of stress among members is not infrequently different from that assumed in the design. For example, in a riveted joint, the load is generally assumed to be equally distributed among the rivets; actual measurements of strain sometimes show considerable differences between the loads carried by different rivets of the group. The uncertainty of distribution of stress between members is especially marked in "statically indeterminate" structures, such as fixed-ended beams, trusses with "redundant" members, and the like.

The science of the mechanics of materials is not yet completely developed. The laws of stress in many common structural members are not yet fully known; for example, the equations commonly used in designing columns are still largely of an empirical nature, different methods of computing stresses in curved beams or in thick cylinders yield varying results.

Different kinds of loading produce varying degrees of structural stress. A load repeated millions of times is far more disastrous than is a steady load, and to some materials (notably wood, metals at elevated temperatures, and some plastics) a long-continued load is more destructive than is one of short duration. The damage caused by shock incident to the operation of machines rarely can be computed with a high degree of exactness.

4. Any machine or structure is liable to be subjected to an accidental or a temporary overload, and some margin of safety should be left to provide for this contingency. A good illustration of such overloads is furnished by hoisting chains and ropes, which frequently are subjected to excessive load on account of the slipping of hooks and hitches.

Consequence of Failure of Material. In determining the maximum safe working stress for any machine member or structural part, the consequences of failure should be taken into consideration. If failure of the piece endangers human life, the allowable working stress is less than for a similar piece whose failure involves merely material damage. If the failure of a particular piece will not cause complete collapse of the structure, and if it can be readily replaced, a relatively high working stress may be allowed.

Factor of Safety. It is obvious that in structures or in machines working stresses must be lower than stresses which will cause structural damage during the period of service of the machine. The tensile strength of a material is obviously such a destructive stress. The yield strength may be the limiting stress for structural or machine parts which are

damaged by appreciable permanent distortion. The endurance limit, or sometimes the fatigue strength, is usually the limiting stress for parts under repeated stress. It is frequently the custom to divide the limiting stress by an arbitrary factor to obtain a working stress and to design the part so that this working stress will not be exceeded during the service period of the machine or structure. This factor is usually called the *factor of safety*. A more appropriate name would be the factor of uncertainty. The uncertainty both of what stresses will be set up in the part under design, and what stresses it can withstand without structural damage, is evident, as shown on the preceding pages.

Values of this factor in common use vary all the way from 2 for steel under steady load to 15 or 20 for timber under long-continued load, repeated load, or very suddenly applied load (shock or impact).[1] The use of this term, factor of safety, may give the designer a false sense of security. If a structure is designed with a factor of safety of 5, it is by no means certain that it will stand up under five times the allowable load. Factor of uncertainty seems to the writers to be a better term than factor of safety.

Standard Allowable Working Stresses. Since the factor of uncertainty does not constitute a positive margin of safety, it has become very general practice to use standard safe stress values in building construction and machine design, rather than to rely upon test results to which a factor has been applied. These standard allowable working stress values are generally fixed by experience. For example, it has become very general practice to allow a working stress of 20,000 lb. per sq. in. for structural steel rolled into rods, plates, and structural shapes. In building construction, standardization of working stresses has proceeded so far that in the building laws of most large cities the maximum allowable working stresses in the common structural materials are definitely fixed.

Table XI(A), (B), (C), and (D) gives allowable working stresses in structural members of steel, cast iron, stone, brickwork, concrete, and wood. The values in the table are recommended stresses given in the publications of the American Institute of Steel Construction, the building codes of New York and Chicago, and in the handbook published by the U. S. Forest Products Laboratory at Madison, Wisconsin.

[1] Much lower values of the factor of safety are sometimes used in airplane design. If an airplane is to carry a heavy load, or even if it is to be able to fly at all, high stresses and lightweight parts are necessary, since each pound of excess material means 1 lb. less of pay load. In place of an adequate factor of safety, sometimes the plane is frequently given a very thorough going-over to discover the initial stages of cracks or of yielding of material. Sometimes the length of service of certain parts is definitely limited, and they are removed after that length of service, even if no sign of structural damage is visible.

TABLE XI. WORKING STRESSES FOR STRUCTURAL MATERIALS

A. STRUCTURAL STEEL

Based on the 1946 specifications of the American Institute of Steel Construction

Metal used in	Type of stress	Working stress, lb. per sq. in.
Shapes and plates	Direct tension	20,000
Cast steel castings	Direct tension	15,000
Butt welds	Direct tension	20,000
Rivets, based on nominal diameter	Direct tension	20,000
Bolts, based on nominal diameter at root of thread	Direct tension	20,000
Columns (either rolled or cast steel)	Direct compression	17,000[1]
Butt welds	Direct compression	20.000
Shapes, extreme fibers in tension	Bending	20,000
Shapes, extreme fibers in compression	Bending	20,000[1]
Rivets, based on nominal diameter	Shearing	15,000
Pins and bolts in reamed or drilled holes	Shearing	15,000
Unfinished bolts, based on nominal diameter	Shearing	10,000
Webs of beams and girders	Shearing	13,000
Weld metal	Shearing	13,000
Rivets	Bearing	32,000
Pins	Bearing	32,000
Turned bolts in reamed or drilled holes	Bearing	32,000
Unfinished bolts	Bearing	20,000

[1] This figure should be diminished by an allowance for buckling failure if the length is more than 5 or 6 times the minimum dimension of the cross section.

TABLE XI. WORKING STRESSES FOR STRUCTURAL MATERIALS. (*Continued*)

B. CAST IRON (COMMON GRAY CAST IRON)

Based on the building codes of New York and Chicago

Type of stress	Working stress, lb. per sq. in.
Direct compression in short blocks	10,000[1]
Extreme tensile stress in flexure	3,000
Extreme compressive stress in flexure	10,000
Shearing stress	3,000[2]

[1] For columns the mean working stress diminishes as the length of the column increases. See column formulas in any book on strength of materials.

[2] The shearing strength of cast iron is greater than the tensile strength; hence, under shear the actual failure is very frequently a failure due to tensile stress, and the maximum allowable working stress in shear is therefore given as equal to the working stress in tension.

In machine building, standardization of working stresses is more difficult than in structural work; the variety of materials used is greater and the conditions of service are even more uncertain. In a large machine-building plant, certain standard allowable stresses are often developed for its particular line of machinery. Tables for allowable stresses and working formulas found in the various engineering hand-

books give valuable suggestions as to the approximate values of working stresses, but such values should not be used without a careful consideration of their limitations when applied to a definite job in designing, especially if a new type of machine or structure is being built. The study of proportions and of probable stresses in successful machines in service is often the best guide for the machine designer in designing a new type of machine for which, of course, allowable working stresses have not yet been standardized.

TABLE XI. WORKING STRESSES FOR STRUCTURAL MATERIALS. (*Continued*)

C. STONE, BRICKWORK, AND CONCRETE

Based on the building codes of Chicago and New York

Compressive stress	Working stress lb. per sq. in.
Rubble masonry, portland cement mortar	140
Ashlar masonry, dressed granite, portland cement, mortar	800
Ashlar masonry, dressed limestone, portland cement mortar	500
Ashlar masonry, dressed marble, portland cement mortar	500
Ashlar masonry, dressed sandstone, portland cement mortar	400
Hollow concrete block, gross area, portland cement mortar	80
Solid concrete block, gross area, portland cement mortar	175
Portland cement concrete	500

Working Stresses for Material Subjected to Repeated Stress. Several factors are highly important in considering working stresses for machine and structural parts under repeated stress, factors which are of much less importance in considering working stresses for parts under static load.

1. For ductile metals under static load the stresses set up at regions of sudden change in section of a part are probably very high in some cases, but the metal near these regions stretches inelastically, distributes a good deal of this excess stress to the metal in its immediate vicinity, and no serious over-all distortion or fracture occurs. Under repeated stress, however, the metal is repeatedly strained locally beyond the yield strength and its ductility is reduced. If stressed often enough, a crack may start there, and will spread, sometimes for a very small distance, but sometimes it will spread to complete fracture. Regions of localized high stress are danger points under repeated stress.

2. The surface condition of the part has rather small effect on the strength under static load, but has a considerable effect on the fatigue strength (resistance to repeated stress).

3. The size of a structural and machine part seems to have some influence on its fatigue strength. Fatigue test results show a considerable "size effect" for specimens up to about 1 in. in diameter, but the effect seems to fall off until after about 1.5 in. in diameter. Further decrease of fatigue strength with increase in size seems to become very

small. However, some tests on large shafts, about 10 or 11 in. in diameter, show very large loss of fatigue strength as compared with specimens, say, 1 in. in diameter. Whether this is a real "size effect" or whether

TABLE XI. WORKING STRESSES FOR STRUCTURAL MATERIALS. (*Continued*)

D. WOOD

Values based on various reports from the U. S. Forest Service. Values of working stress given in this table are for *common grade* wood. Values for "select" grade would be somewhat higher. Stress values in pounds per square inch.

Values for compressive strength of wood parallel to the grain depend on the ratio of length to thickness of the piece of timber. See the "Wood Handbook" of the U. S. Forest Products Laboratory, pp. 162–168, June, 1940.

Species	Continuously[1] dry		Occasionally[1] wet, but quickly dried		Continuously[1] damp or wet		Properties not varied with conditions of exposure	
	Extreme fiber stress	Comp'n stress across grain	Extreme fiber stress	Comp'n stress across grain	Extreme fiber stress	Comp'n stress across grain	Horizontal shear	Modulus of elasticity
Western red cedar	720	200	600	150	570	125	64	1,000,000
Southern cypress	1,040	350	830	250	680	225	80	1,200,000
Douglas fir:								
Coast region	1,200	325	980	225	750	200	72	1,600,000
Rocky Mountain region	880	275	680	225	530	200	68	1,200,000
Hemlock:								
West coast	1,040	360	830	225	680	200	60	1,400,000
Eastern	880	300	680	225	600	200	56	1,100,000
Oak: red and white	1,120	500	900	375	750	300	100	1,500,000
Pine:								
Southern	1,200	325	980	225	750	200	88	1,600,000
Norway	880	300	760	175	600	150	68	1,200,000
Redwood	960	250	760	150	600	125	56	1,200,000
Spruce	880	250	680	150	600	125	78	1,200,000

[1] *Continuously dry* wood is wood used in interior or protected construction not subjected to excessive dampness or high humidity. *Occasionally wet, but quickly dried* wood used in such structures as bridges, trestles, grandstands, bleachers, or open sheds. *Continuously damp or wet* wood is wood exposed to waves or tidewater, or in contact with earth, or used in locations in a building where the wood is liable to be continuously wet.

there was serious loss of strength, for reasons as yet unknown, is a problem at present unsolved.

Theoretical Concentration of Stress at "Stress Raisers." To irregularities of form of a part which cause high localized stress, the late Dr. H. W. Gillett gave the very apt name "stress raisers." A convenient

index of the destructive action of a stress raiser is a "theoretical" *stress-concentration factor*, the ratio between the stress computed by the formulas of the advanced theory of elasticity, or by experimental methods at a hole, a notch, or other stress raiser, and the computed stress in the specimen, or structural part, if there had been no stress raiser in it.

Theoretical Stress Concentration and Actual Strength Reduction. By the use of the formulas of the mathematical theory of elasticity, and by the use of devices for the experimental solution of some of the extremely complex differential equations involved in the application of that theory, it is possible to get theoretical values of the stress-concentration factor for a number of typical stress raisers. Theoretical values of stress concentration may be obtained by viewing by polarized light specimens made of some of the transparent plastics. When specimens are tested in fatigue, the effect of stress raisers in reducing fatigue strength has never been found greater than that indicated by theory. The discrepancy between theory and test results varies for different metals, but in the absence of sufficient data to determine actual strength-reduction factors for various metals, the best general rule to follow is to make allowance for the theoretical stress concentration, a procedure which will be on the safe side.

The following paragraphs discuss very briefly the effect of several typical stress raisers.

Holes. A small hole in a machine or a structural part under tension, compression, or flexure sets up localized stress at the edge of the hole. By the formulas of the theory of elasticity the stress-concentration factor can be computed. For holes which are less than one-sixth the width of the piece, the theoretical stress-concentration factor is about 3. For a small radial hole in a shaft under torsion, the theoretical stress-concentration factor is 4.

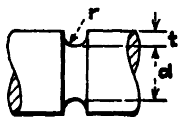
Notches and Grooves. Table XII(*a*) gives values for the theoretical stress-concentration factor for notches or grooves in shafts under bending. The values given are for notches with parallel sides (flank angle 180 deg. or 2π radians). For notches with sloping sides, the stress-concentration factor is less than for notches with parallel sides, and the use of the theoretical stress-concentration factor as a measure of actual strength reduction under repeated stress is "on the safe side." Table XII(*b*) gives values of theoretical stress-concentration factors for notches or grooves in shafts under torsion. Tables XII(*a*) and (*b*) are based on a mathematical analysis of stresses by Neuber (see reference 8 at end of chapter).

Fillets at Shoulders of Shafts. Table XII(*c*) gives values of theoretical stress-concentration factors for fillets at shoulders of shafts under bend-

TABLE XII. "THEORETICAL" STRESS-CONCENTRATION FACTORS FOR FILLETS AND NOTCHES IN SOLID ROUND SHAFTS

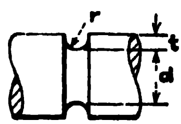
(a) Theoretical stress-concentration factors for flexural stress at notches, based on mathematical stress analysis by Neuber

t/r	r/d									
	0.02	0.04	0.06	0.08	0.10	0.15	0.20	0.30	0.40	0.50
0.25	1.95	1.90	1.81	1.75	1.68	1.56	1.48	1.36	1.30	1.25
0.50	2.27	2.13	2.01	1.89	1.79	1.61	1.51	1.37	1.31	1.25
1.00	2.65	2.38	2.16	2.00	1.85	1.64	1.53	1.38	1.31	1.25
2.00	2.95	2.58	2.30	2.06	1.90	1.66	1.54	1.39	1.31	1.25
5.00	3.45	2.64	2.38	2.10	1.94	1.68	1.55	1.39	1.31	1.25



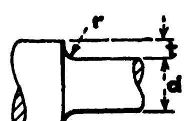
(b) Theoretical stress-concentration factors for shearing stresses in notched shafts in torsion, based on mathematical stress analysis by Neuber

t/r	r/d									
	0.02	0.04	0.06	0.08	0.10	0.15	0.20	0.30	0.40	0.50
0.25	1.46	1.40	1.37	1.33	1.30	1.21	1.19	1.14	1.11	1.10
0.50	1.62	1.55	1.45	1.38	1.33	1.22	1.20	1.14	1.11	1.10
1.00	1.80	1.63	1.50	1.40	1.35	1.24	1.20	1.15	1.11	1.10
2.00	1.98	1.70	1.55	1.42	1.37	1.25	1.20	1.15	1.11	1.10
5.00	2.30	1.80	1.59	1.45	1.38	1.25	1.20	1.15	1.11	1.10



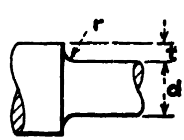
(c) Theoretical stress-concentration factors for flexural stresses at fillets in shafts, based on data of photoelastic tests made by Prof. M. M. Frocht

t/r	r/d									
	0.02	0.04	0.06	0.08	0.10	0.15	0.20	0.30	0.40	0.50
0.25	1.50	1.48	1.47	1.45	1.43	1.38	1.35	1.30	1.25	1.20
0.50	1.70	1.68	1.65	1.60	1.55	1.49	1.40	1.33	1.26	1.21
1.00	1.96	1.90	1.85	1.74	1.60	1.50	1.45	1.34	1.27	1.21
2.00	2.35	2.18	2.05	1.87	1.75	1.53	1.48	1.35	1.27	1.21
5.00	3.00	2.56	2.29	2.00	1.81	1.56	1.50	1.35	1.27	1.21



(d) Theoretical stress-concentration factors at fillets in shafts in torsion, based on proportions between (a), (b), and (c) and checked by some results of electrical drop-of-potential tests on model specimens by Jacobsen

t/r	r/d									
	0.02	0.04	0.06	0.08	0.10	0.15	0.20	0.30	0.40	0.50
0.25	1.12	1.11	1.11	1.10	1.10	1.10	1.09	1.08	1.07	1.06
0.50	1.22	1.20	1.19	1.17	1.16	1.12	1.10	1.10	1.08	1.06
1.00	1.33	1.29	1.25	1.22	1.19	1.14	1.13	1.11	1.09	1.06
2.00	1.52	1.44	1.36	1.30	1.26	1.19	1.16	1.13	1.10	1.06
5.00	2.00	1.72	1.52	1.38	1.30	1.19	1.16	1.13	1.10	1.06



ing. It is based on the data of photoelastic tests made by Prof. M. M. Frocht of the Illinois Institute of Technology.[1] Table XII(d) gives values for theoretical stress-concentration factor for fillets at shoulders of shafts under torsion. It is based on proportions between the values given in Tables XII(a), (b), and (c) and has been checked against the ranges of values found by Jacobsen,[2] who used an electrical resistance method of stress measurement.

Keyways in Shafts. In a shaft under torsion the greatest theoretical stress concentration at a keyway is at the reentrant angles a and b in Fig. 44. If the corners were absolutely sharp the stress would be, theoretically, infinite. Actually all such corners have some radius of curvature, but the theoretical stress concentration as found by the soap-film method of Griffith and Taylor[3] gave values as high as 5 for some models of keyways. Actual fatigue tests by Gough[4] showed values ranging from 1.14 for mild steel to 1.27 for medium-hard steel.

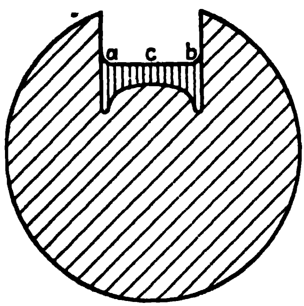


FIG. 44. Concentration of shearing stress at keyway in shaft.

Screw Threads. Tests by Moore and Henwood at the University of Illinois[5] indicate a strength-reduction factor of 3 for U.S. Standard screw threads on structural steel and of 4 for screw threads on heat-treated alloy steel. A slightly lower factor was found for the Whitworth standard threads. However, these tests were all on 3/8-in. threads. Larger threads might show different values for stress concentration. R. R. Moore[6] has made tests which show that the strength-reduction factor for a single groove with the shape of a screw thread is distinctly higher than the strength-reduction factor for a screw thread of several turns. A length of thread beyond that required for fastening bolts adds to the fatigue strength of a bolt. The same effect can be obtained by turning down a short length of the bolt at the end of the thread to a diameter no greater than that at the root of the thread.

Effect of Localized Compressive Stress. Pressures between wheels and the rails or surfaces on which they run, pressures between mating

[1] *Trans. A.S.M.E.*, Vol. 57, pp. A-67 and A-68, 1935.

[2] *Trans. A.S.M.E.*, Vol. 47, p. 619, 1925.

[3] *Proc. Brit. Inst. Mech. Engrs.*, October–December, 1917.

[4] Reports and Memoranda No. 864, Aeronautical Research Committee, British Government, London.

[5] *Univ. Ill. Eng. Expt. Sta. Bull.* 264.

[6] *Proc., A.S.T.M.*, Vol. 26, Part II, p. 255, 1926.

gear teeth, and pressures between ball and race in ball bearings, are three examples of parts in which there are very high localized compressive stress at bearing points or lines. Heinrich Hertz,[1] showed that at surfaces of contact there are compressive stresses in three directions, normal to the surfaces in contact, longitudinal, and transverse. Mathematical analysis and tests (see reference 5 at end of chapter) show that as the distance below the surfaces increases, the normal stress diminishes but remains compressive while the longitudinal and transverse stresses diminish more rapidly, pass through zero and become tensile stresses below a short distance below the surface. This combination below the surface indicates quite high shearing stresses due to high localized compression as well as tensile stresses. It seems that cracks, pitting, and sometimes fracture, may be caused by these subsurface tensile stresses, or by the subsurface shearing stresses, or perhaps by the joint action of both.

Effect of Surface Conditions on Fatigue Strength. The difference between the fatigue strength of polished specimens and specimens with rough-turned or hot-rolled surfaces may be as great as 30 per cent of the value for polished specimens. This statement is based on data from a number of testing laboratories, American and foreign. Corrosion without stress may reduce the fatigue strength as much as this, or even more. Simultaneous corrosion and repeated stress may reduce the fatigue strength to a value of k less than 25 per cent of the value for polished specimens not exposed to corrosive media while being subjected to repeated stress.

Methods of increasing fatigue strength by surface treatment of structural and machine parts include carburizing, nitriding, localized heat treatment by flame or by induction hardening, cold-rolling, and shot-peening. No advance estimate of the relative increase of fatigue in these processes can be made, since so many variable factors are present. In each case *improperly controlled treatment* may actually *reduce* the fatigue strength.

Characteristic Appearance of a Fatigue Fracture. Figure 45 is from a photograph of a fatigue failure in a rotating shaft under flexure. Circumferential fatigue cracks started at the cross section shown and spread *inward.* As the cracks spread, they opened and closed under the reversed flexure, and the two walls of each crack battered each other to a fairly smooth surface. The spread of the fatigue cracks went on, like the progress of a minute hack-saw cut, until the only sound metal left at the cross section was a small circular core. This reduced area proved unable to stand the load on it and suddenly pulled in two, leaving a bright,

[1] H. Hertz, "Miscellaneous Papers," 1896.

jagged, "crystalline" surface. The two surfaces, the battered-smooth surface showing the progress of the fatigue cracks, and the crystalline surface showing the extent of the final sudden break, are characteristic of fatigue failures.

Examples of Parts That Fail. Drill rods for drilling wells are subject to occasional fatigue failures. In very long rods an appreciable time is required for the transmission of stress from top to bottom, and interference waves of stress are set up by successive impulses. This means the development of high stress at certain sections of the rod.

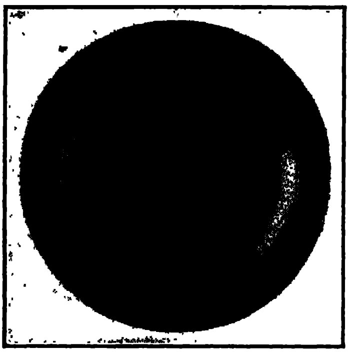


Fig. 45. Fracture of a rotating shaft under reversed bending.

Tie rods in airplanes are subjected to vibration, and hence to a certain range of repeated stress. When fatigue failures occur, they are usually at sharp shoulders or at screw threads.

Bolts and screws under repeated stress show occasional fatigue failures starting at the roots of threads.

Wire ropes bent around sheaves are subjected to repeated (sometimes reversed) bending stress. Fatigue failure is shown by the breaking of individual wires and, if the rope is subjected to a careful periodical inspection, it can usually be replaced before a disastrous failure occurs.

"Live" (rotating) axles under transverse load are subjected to cycles of reversed bending and occasionally fail, practically always near the fillet at a shoulder, or near the edge of a bearing or a wheel seat. Such failures in service are likely to cause serious disaster. On some railways periodical inspection of axles for incipient cracks has reduced axle failures in service almost to the vanishing point.

Shafts for transmitting power are subjected to repeated torsion, and frequently to reversed bending as well. Fatigue failures in shafts frequently start at the root of a keyway, where there is a high concentration of torsional stress. Fatigue failures in crankshafts sometimes occur at the fillet joining of shaft and crank arm.

Piston rods sometimes develop fatigue failures in service, the fracture usually starting at the root of a thread or at a sharp shoulder.

Springs are designed to absorb the energy of repeated loading. Flat springs occasionally fail under repeated flexure, the fracture usually occurring at the point of bearing of one leaf on another. Coil springs occasionally fail under repeated axial load, which sets up torsional stresses in the coils. Valve springs in internal-combustion engines,

working as they do under high temperature, are especially liable to fatigue failure. Surface decarburization is a frequent cause of fatigue failures in springs.

Airplane propellers occasionally develop fatigue failures. They are subjected to a wide range of complex stresses, including torsional stresses. Propellers made of wood are subjected to repeated shearing stresses along the grain of the wood.

Thin rotating disks, such as are used in some steam turbines, are liable to "flutter" laterally at certain speeds. This sets up cycles of reversed lateral bending, and disastrous failures have been caused by this action. Such failures usually start at a hole in the disk, a deep tool mark, or other stress raiser. Such accidents are best avoided by designing the disks so that there are no holes in them at points of high stress, by polishing the surfaces of the disks, and by so proportioning them that the lateral vibration (or the simpler harmonics of that vibration) will not synchronize with the running speed of the turbine (see Fig. 23).

The failure of a few blades in a steam turbine does not always mean a disaster; many turbines run for a considerable time with some blades broken out. The fatigue failure of blades is, however, a source of expense and vexatious trouble.

Welded joints, especially fusion-welded joints (electric-arc welds and oxyacetylene welds), if made under carefully controlled conditions and with welding rods coated with some substance which, under the heat of welding, gives off a nonoxidizing gas which forms a protective cloud around the weld, are produced with both static strength and fatigue strength very nearly equal to that of the metal welded. However, welds made without careful supervision, or without coated rods, can hardly be counted on for more than 50 per cent of the fatigue strength of the welded metal. For structural welded joints, pressure vessels, and railroad rails a fatigue strength based on a relatively small number of cycles of stress (100,000 to 2,000,000) is a satisfactory index. In important pieces of welded construction it is becoming increasingly common to examine welded joints with X rays to disclose internal cracks.

Detection of Fatigue Cracks before Failure Occurs. Wherever it is feasible to make periodic examinations of a shaft, an axle, a disk, or other machine part, fatigue cracks can frequently be detected in their early stages and the part replaced before a disaster occurs.

Fatigue cracks can be detected by direct examination of the surface of the suspected piece or by the use of a small magnifying glass. They can also be detected by magnetizing a steel part, then sprinkling very fine iron dust over it. The magnetic poles formed at a crack gather a fine line of dust and outline the crack. Special equipment for this

magnetic testing for cracks is available under the trade name of Magnaflux.

If the surface of a machine part is rubbed with oil, the oil wiped off, the surface then coated with a thin paste of whiting, and the part then mounted on blocks and struck smartly so as to set up bending stresses, the location of a crack will be shown by the oil stain on the whiting. When the oil is wiped off the surface, some remains in any small cracks, and the bending stresses squeeze it out, discoloring the whiting.

A very promising method of detecting incipient fatigue fractures has been applied to railroad rails in service by Sperry. A test car travels along the track at a slow speed, and from a generator in the test car a current of several thousand amperes is passed through a length of rail of about 4 ft. Between the brushes conveying this current between generator and rail are placed pairs of small coils which, as they move along,
erator and rail are placed pairs of small coils which, as they move along,
have set up in each pair opposing currents from the current in the rail, and the magnetic field caused thereby. If there is a small imperfection in the interior of the rail head, the direction of lines of force around the rail is changed, and the balance of currents is broken between the coils of each pair. The current flowing in the coil circuit is amplified by radio amplification methods until it is strong enough to operate a small recording galvanometer. It is claimed that in a full-size rail a flaw or fissure only 1/4 in. in diameter can be detected. High-frequency sound waves are sometimes used to detect the presence of small cracks deep in the interior of steel locomotive and railroad-car axles. Such a sound wave will tend to travel in a straight line from its source (traveling through the metal at sonic velocity[1]) and to be reflected from any open surface or from any crack within the metal. When this method is applied, the sound waves are induced by a small point source, called a *transducer*, and are directed along the axis of the axle, or parallel to the axis. In a good axle, such a sound wave will travel to the far end, be partly reflected by the free surface there, and return. The time interval between the incidence of a particular wave and the return of the "echo" will then be the sonic velocity divided by twice the axle length. If, however, some crack exists within the axle, there will be reflection from the near surface of this crack, and an echo from *this* surface will return to the starting point in a shorter time interval. The time required for each wave to travel down the axle and be reflected is measured by a cathode-ray oscilloscope, and a skilled operator will be able to interpret properly the changes in the oscilloscope pattern, much as a radar operator will be able to interpret the radar oscilloscope patterns.

[1] Ultrasonic waves are also used.

Cycles of Stress in Service. In laboratory fatigue tests a specimen is subjected to repeated cycles of stress, each cycle involving the same range of stress. In service, structural and machine parts are subjected to very many cycles of working stress and to occasional cycles of overstress. The occasional cycles of overstress, if above the endurance limit, start fatigue cracks when repeated enough times. During the first few thousand cycles of stress these cracks usually cannot be detected by any means now available; they are so small that the static-strength properties of the material are not appreciably affected. However, there are no data which indicate that such minute cracks once started are "healed" by periods of rest; on the other hand, once such cracks are started they will spread under cycles of stress well below the original endurance limit of the metal.

Test data on this point are very few, but recent tests at the University of Illinois on car-axle steel and on rail steel indicate that if fatigue cracks are once started they may spread under cycles of stress as low as 50 per cent of the original endurance limit.

Very little can be said as to the length of time or the number of cycles of stress necessary to cause failure of a machine part; however, as the fatigue cracks spread, their rate of growth is accelerated. If subjected to stresses beyond the endurance limit, two specimens from the same bar of metal, tested under as nearly identical conditions as can be secured in the laboratory, will show wide variation in "life." The critical stress below which progressive fracture will not occur is fairly well defined for all, or very nearly all, commercial metals; the length of life of a part repeatedly stressed beyond the endurance limit is not at all well defined.

Fatigue Failure of Nonmetallic Materials. The test data for nonmetallic materials under repeated stress are very few. A few tests have been carried out on wood under reversed flexure, and the meager results suggest that the endurance limit for wood may be as low as one-quarter the computed ultimate stress in flexure (modulus of rupture). That is, for wood the indications are that the endurance ratio may be as low as one-quarter (see references 3 and 6 at end of chapter).

For concrete under compression, under cycles of stress varying from zero to a maximum ($R = 0$), the fatigue strength less than 1,000,000 cycles of stress is about 50 per cent of the static compressive strength, either for beams or for compressive cylinders. Periods of rest seem to have only a temporary effect on the recovery from deformation and do not change the fatigue strength appreciably (see reference 6 at the end of chapter).

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8. NEUBER, H.: "Theory of Exact Stress Calculation," Edwards Bros., Inc., Ann Arbor, Mich., 1946.
9. LIPSON, NOLL and CLOCK: "Stress and Strength of Manufactured Parts," McGraw-Hill Book Company, Inc., New York, 1951. This book contains 139 charts for determining stress-concentration factors.

See also pocket books and handbooks for civil, mechanical, and architectural engineers, building ordinances of cities, handbooks of steel companies and firms producing nonferrous metal shapes and plates.

Questions

1. Define working stress, factor of safety, structural damage.

2. State the four theories of the cause of structural damage. Which theory or theories seems to fit best the results of tests and service performance? Which theory is commonly used? Why?

3. Name several reasons why the working stress must be less than the ultimate strength of the material as determined by tests.

4. Name a structural or machine part in which structural damage can be done although the extreme stress is less than the yield strength of the material. Name a part in which damage is done when the yield strength is exceeded. Name one which is likely to fail by "creep." Name one which is likely to fracture under repeated stress.

5. Do the building codes of the town where you live fix allowable stresses for any materials of construction? If so, what ones?

6. How would you determine the allowable stress for an aluminum alloy to be used as a material for I beams?

7. Give your opinion of the suitability of the material used for railway and highway bridges in your town.

8. Assuming that a "live" axle for a truck and a simple I beam for a bridge are built of the same material, in which would the allowable working stress be greater? How much greater? Explain.

9. In your town or city, is the construction of wooden frame buildings justifiable? Give a reason for your answer.

10. What different metals are used in (a) a small power pump, (b) a gasoline engine, and (c) a dump cart? Why is each material used?

11. Why is the "theoretical" stress-concentration factor larger than the actual strength-reduction factor?

12. Under repeated tensile stress which is stronger, a bolt screwed in as far as its thread will allow it to go, or a bolt of the same size and material which is screwed in until five threads are visible? Explain.

13. A shaft with a keyway is subjected to reversed *bending* and not to torsion. Does the keyway then act as a "stress raiser"?

14. A steel rod is strengthened by hardening a very shallow depth of metal at its surface. Will the strength in tension be as much increased as the strength in bending? Will the strength of a large rod hardened to the same shallow depth be increased by the same percentage as would be the case for a smaller rod? Explain.

15. Could a fatigue crack in the blade of a steam or gas turbine be detected before failure as readily as a crack in a railroad rail? As readily as a crack in the structure of an airplane? Explain.

CHAPTER VIII

THE FAILURE OF METALLIC MATERIALS BY CORROSION AND BY WEAR

Importance of Corrosion and Mechanical Wear. Each year in the United States millions of dollars' worth of damage to iron and steel structural parts is caused by corrosion, and other millions are expended in replacing worn-out parts of machines. Damage by either corrosion or wear takes place gradually and rarely causes sudden or dramatic structural disaster. Usually parts damaged by corrosion or by wear can be repaired or replaced before disastrous failure takes place. However, it may be noted here that this is not true for parts subjected to the simultaneous action of corrosion and repeated stress, or to pressure vessels, such as steam boilers, whose seams may be subjected simultaneously to intensified corrosion and localized stress.

The lessening of the annual bill for damage by corrosion and mechanical wear is very important in the economics of engineering materials. At the present time neither of these problems can be treated in the quantitative manner which is possible in treating problems of failure due to stress and strain alone, and this chapter gives a brief qualitative discussion of these two types of failure of metallic materials, especially of iron and steel.

The Mechanism of Corrosion. The common metallic materials of construction readily go into solution at first contact with water containing dissolved oxygen or with moist air. The initial rate of solution is quickly retarded by a film of hydrogen formed on the iron and by films of other products of corrosion. These films are a few atoms thick and usually are invisible. If the protective film formed is sufficiently dense and sufficiently tough, the progress of corrosion may be stopped or very greatly retarded. Free oxygen, if present, tends to combine with the hydrogen film as it forms, thus permitting the further progress of corrosion, and any acids present also tend to destroy the protective films.

Types of Corrosion. The corrosion of metallic materials may be divided into five classes: atmospheric, water immersion, soil, chemicals other than water, and electrolytic.

In atmospheric corrosion there is always present a great excess of oxygen and the rate of corrosion is largely determined by the quantity of moisture in the air and the time of contact of moisture with iron. Probably iron would not corrode in absolutely dry air.

For metal immersed in water the amount of oxygen dissolved in the water is a factor of prime importance. Probably even iron would not corrode in absolutely pure water with no dissolved oxygen in it. If water has a slightly acid reaction the tendency to corrosion is, in general, increased, while water with an alkaline reaction usually has little corrosive action on iron except for highly concentrated solutions.

In soil corrosion and corrosion by chemicals the particular ingredients coming in contact with iron are of more importance than the variations of composition of the ordinary structural iron and steels.

Corrosion by electrolysis due to stray currents from power circuits may be very disastrous, but in nearly all cases it can be prevented by suitable electrical precautions.

Protective Coatings against Corrosion; Paint. For ordinary structural iron and steel the commonest protection against corrosion is a coat of paint. Such a coat is mechanically weak, it cracks and wears out, so that to be effective it must be renewed every few years. Clean metal is essential for the placing of an effective coat of paint. All rusted spots should be cleaned off with a wire brush or a sand blast; else corrosion will go under the new coat of paint. Asphalt or coal tar makes a good protection against water. A layer of rich concrete 2 in. thick is an excellent protective coating for structural steel. At cracks in protective coatings corrosion is likely to proceed at a rapid rate and such local corrosion is likely to take the form of deep disastrous *pitting* rather than a thin comparatively harmless coat of rust. Cracked protective coatings have lost most of their value.

Other Protective Metal Coatings. Coatings of the noble metals deposited by electrolysis would give excellent protection against corrosion, but are too expensive for structural use. Plated-on coatings of nickel, chromium, cadmium, and zinc are used to protect against corrosion. Their value is largely in the relative toughness of the film of oxide formed on the surface and the protection which this film gives against the progress of corrosion. Coatings of molten zinc and of tin are used to protect iron and steel against disastrous corrosion, yielding the common products, galvanized iron and tin plate, and zinc is sometimes plated on by electrolysis.

Protection against corrosion is also secured by sandwiching sheet or plate metal between two thin layers of a corrosion-resisting metal. The base metal and the corrosion-resisting metal are bonded together by rolling at a suitable temperature. Such composite metal sheet or plate is known as "clad" metal, and the "cladding" may be on one side of the base metal or, more commonly, on both sides of the base metal, as indicated above. The base metal and the cladding should have as nearly

the same modulus of elasticity as possible to avoid internal strains and distortion in the finished product. Nickel-clad steel, monel-clad steel, inconel-clad steel and high-strength aluminum alloys clad with pure aluminum are in use.[1] The thickness of the sheet of cladding ranges from about 5 to 20 per cent of that of the base metal. Clad aluminum, known by the trade-mark name of Alclad, owes its effectiveness to the fact that pure aluminum is more resistant to certain types of corrosion than are the high-strength aluminum alloys.

Corrosion and Stress; Corrosion-fatigue. Metals under stress, especially stress beyond the elastic strength, corrode more rapidly than do unstressed metals. Certain boiler waters containing a high alkali content plus a silicate seem to be likely to cause dangerous corrosion followed by cracking at points of high localized stress around the rivet seams of the boiler shell. The "caustic embrittlement," as it is called, can usually be prevented by adding chemicals, usually sulfates or phosphates, to the boiler feed water.

In 1917 Haigh at the British Naval Academy laboratories at Greenwich made fatigue tests of certain brasses while in contact with strong corrosive agents. He found a marked reduction in fatigue strength. A few years later McAdam began an exhaustive study of the effects of stress on corrosion. It had been found that corrosion *without stress* reduced the fatigue strength of metals by as much as 30 per cent, probably on account of roughening the surface and making stress-raising pits in it. McAdam found that *simultaneous* corrosion and stress are far more dangerous than either acting alone. His work and that of others raised a doubt as to whether under simultaneous corrosion and stress there is any clearly defined endurance limit. If there is, it is very much smaller than the endurance limit for metals not subjected to corrosion. Furthermore, with the exception of the special corrosion-resisting steels, simultaneous corrosion and repeated stress, "corrosion fatigue" as it is called, reduces the fatigue strength of heat-treated steels to a value but little, if any, larger than that for ordinary soft steels.

The damage done by simultaneous corrosion and repeated stress is best explained in terms of the breaking of the protective film of corrosion products formed when corrosion takes place. If that film is brittle, it readily breaks under repeated stress and a new surface is opened up to corrosion, which promptly takes place; further cycles of stress break the film formed where the initial film cracked, and so the cycle of increasing damage goes on, until a fatigue crack starts at the root of a corrosion notch and spreads to fracture.

The value of protective coatings depends on their toughness and,

[1] Monel and inconel are alloys of nickel.

if they are metallic coatings, on the toughness of the protective film formed on them by oxidation. The tough film formed on chromium gives it great value as a protective coating against corrosion. Steel with a high chromium content resists corrosion fatigue somewhat better than ordinary structural steel.[1] Even a coating of thick grease gives a considerable degree of protection against corrosion fatigue. Coats of "elastic" varnishes and of rubber cement have also been found to afford some protection.

A method of protection against corrosion fatigue has been described by Speller, McCorkle, and Mumma (see reference 2 at end of chapter). This method, which is available in certain special cases, consists of treating the corroding water with a chemical which will cause it to form the protective film on a metal very rapidly, more rapidly than it will be broken by successive cycles of stress. Certain strong oxidizing agents, such as potassium bichromate, have been found effective by these experimenters.

As noted in the opening paragraphs of this chapter, no tabulated values for damage by corrosion or of resistance to corrosion are available. The present-day solution of corrosion problems seems to consist of finding tough protective coatings for materials exposed to corrosive agents, especially to metals exposed to simultaneous corrosion and stress.

The Nature and Importance of Mechanical Wear. In nearly all cases the failure of materials by mechanical wear under abrasion occurs gradually, the progress of wear is evident, and the failure is not a definitely defined event, but one whose occurrence is a matter of judgment on the part of the user of the material. Failure by wear rarely involves a structural disaster, although shelling may involve repair or replacement of a part.

Many examples of failure of materials by wear will occur to the student. Although an individual case of failure by wear is rarely a serious matter, the aggregate of failures by wear is a very large item in the economics of engineering materials.

One form of mechanical wear may be observed in a rotating shaft at the point where it enters a bearing. There is formed at that section of the shaft a very high localized stress at the edge of the bearing and a fine dust of minute oxidized particles comes off from the shaft. This dust is sometimes known as "cocoa," and unless the shaft has a smaller diameter away from the bearing than at the bearing, the fine dust locates the danger section for fracture.

[1] There are in use today a number of "low-alloy" steels, some of which have a small chromium content. These low-alloy steels do not seem to be appreciably more resistant to corrosion fatigue than ordinary structural steels.

In general, mechanical wear seems to act by shearing off or pulling off minute pieces from the rubbing surfaces. A typical case of structural damage to a railway rail by wheel loads by wear is shown in Fig. 46. The dotted lines show the original shape of the rail head, and the wearing away of steel on the top and on the right hand side is evident, as is the distortion on the left hand side.

In the upper right hand corner of Fig. 46 at C and C' can be seen the beginning of the progressive "shelling" fracture along the rail. Such shelling fractures are rather rarely found before the rail has worn out, but they are more dangerous than the gradual wearing away of the metal, and *may* start a fracture across the entire cross section of the rail, although this rarely happens.

Fig. 46. Wear of railroad rail after service.

It seems probable that oxidation of particles is a factor in the mechanical wear of rubbing metal surfaces. It is often noticed that on the surface of the tread of unused railroad track a visible coating of iron oxide soon forms, but when trains are once again run over this track the oxide dust is rubbed off and blown away. Spots of oxidized steel can be seen on rails at stations, where the brakes have been suddenly applied, causing slip of the wheels and a rapid oxidation over a small area on the rail surface.

Smooth Wear and Pitted Wear. When certain metals have rubbing contact, wear takes place with the formation of pits. An illustration of such wear is found in the pits caused when soft steel rubs on soft steel. The toughness, or perhaps the ductility, of the soft steel tends to cause relatively large particles to be torn out. Such pitting is much less in evidence when soft steel rubs on brittle cast iron, or when shafting steel rubs on a bronze or babbitt bearing which is made up of relatively hard particles imbedded in a matrix of softer metal.

Temperature also seems to play a part in wear. Under a rubbing load heat is developed, and at the minute points of actual contact temperatures may be developed well above the average temperature of the rubbing surfaces. Even a cursory examination of a stretch of railroad track shows many pitting scars at locations near stations or switches where the brakes are frequently applied, increasing the temperature at the spot being rubbed. Railroad men speak of these spots as "burns." The

well-known "burning out" of bearings is another example of this tendency to pitting wear under increase of temperature.

Wear of Lubricated Surfaces. The wear of lubricated surfaces depends largely on the presence or absence of a film of lubricant between them. If a perfect film is always present, wear is almost, if not quite, negligible. In such cases there seems to be a "wear limit"—a critical intensity of load above which the film of lubricant is squeezed out. This limit depends on a number of factors—viscosity of lubricant (which, in turn, depends on temperature), intensity of pressure, relative speed, and smoothness of rubbing surfaces.

Fracture Wear and Cold-work Wear. The removal of fine particles of metal under rubbing wear and the deformation of rubbing surfaces by a flow of metal seem to be two separate phenomena. The deformation by cold-work somewhat strengthens the metal but embrittles it and thus affects the tearing off of particles, as well as contributing to the distortion of the metal by flow.

Wear and Hardness. In considering the effect of hardness on wear it must be kept in mind that "hardness" is a term used to cover several quite different properties of metal. There is the hardness measured by the size of permanent indentation left by a given sized steel ball or diamond point after a given load has been applied and released; the hardness measured by the width of scratch by a cutting point under a given pressure; the hardness measured by the difficulty of machining or filing; the hardness measured by amount of abrasion under a given load and a given velocity of rubbing. In general, the greater the hardness measured by any of these means the less the wear—but there are many exceptions to this rule. The superior wearing qualities of bearings made of bronze, of rather soft bearing metals, or of plastics, over bearings made of steel is an example of such an exception.

Tests for Wearing Qualities. Numerous wear-testing machines have been designed and used. In general a wear-testing machine consists of a means for applying a load to a specimen of material which is rubbed at a given speed over another piece of material or over an abrasive surface. The amount of wear after a given amount of rubbing is measured either by loss of weight of the specimen or by change of form. If change of form is measured, both the wear due to tearing off pieces of material and that due to cold-work are measured. If loss of weight is the criterion, only the wear due to tearing off of particles of metal would be indicated.

The difficulty of establishing any standards for wear testing is very great. Wear tests must, in general, be accelerated tests, and a wear test of two metals under a heavy load is not at all certain to rate them in the same order of merit as a longer wear test under a light load. Then, too,

wear tests of materials against different abrasive surfaces may give quite different orders of merit.

This is illustrated by recent wear tests of gear teeth. Wear tests were first used which would produce measurable wear in a short time, and various metals were tested. When tests were made under lighter loads, some of the metals that had shown rather heavy wear under heavy loads showed no appreciable wear under light loads, and some of the metals that showed little wear under the heavy-load test continued to show appreciable, although reduced, wear under the light-load test. There seemed to be a sort of "wear limit"—a critical intensity of load below which wear was very slight indeed. The relative values of "wear limit" for various metals could not be predicted from the behavior under a short-time, heavy-load test.

Tests for elastic strength, for creep strength, and for resistance to fracture are by no means wholly satisfactory, but wear tests available today are even less satisfactory for predicting the behavior of materials in service. The development of reliable wear tests is one of the unsolved problems in the study of engineering materials.

Repairing Worn Parts by Welding. Autogenous (fusion) welding has been used to build up worn parts to their original size. Worn shafts, railroad rails, and other structural and machine parts have been thus repaired. In some cases the results have been satisfactory, but in others fractures developed (either during welding or later in service) in the vicinity of the junction surface of weld metal and base metal. Temperature differences between the hot weld metal and the relatively cooler base metal set up strains which may cause fracture, and the cooling of the region near the weld sometimes embrittles the metal. The satisfactory use of welding to build up worn parts involves a complicated technique of preheating, avoiding the oxidation of metal during welding,[1] and controlled cooling. At present no general rules can be given; each job must be studied by itself.

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[1] One way of preventing such oxidation is by using a welding rod coated with a substance which, when heated, gives off a nonoxidizing gas which forms an "atmosphere" around the weld (see p. 111).

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Questions

1. Name several structural or machine parts in which failure by corrosion is quite probable.

2. Name several structural or machine parts which may be expected to wear out after a limited period of use.

3. Read Oliver Wendell Holmes's poem "The Deacon's Masterpiece" (commonly known as "The Wonderful One-hoss Shay") and criticize the deacon's method of choosing the materials for different parts of the vehicle.

4. Describe the development of corrosion in a metal which is not under stress. What difference does the addition of stress make in the process? What further difference does repeated stress make?

5. What method of preventing corrosion would you use in the following: (1) the engine valves in an automobile, (2) the members of the truss of a highway bridge, (3) the screws in a screw-power testing machine, (4) the leaves of the springs in an automobile, (5) piston rings in an engine cylinder, (6) gear teeth in contact?

6. Why do the treads of railway rails rust if trains are not passing over them, and why do they not rust while trains are running over them frequently?

7. Compare chromium with zinc and with tin as a corrosion-resisting coating.

8. Explain under what conditions the addition of an oxidizing agent to water may prevent failure by a combination of corrosion and stress.

9. Define corrosion fatigue. What failures of structural or machine parts have you seen which may have been caused by corrosion fatigue?

10. Compare failure by abrasive wear with fatigue failure under repeated stress. In what ways may abrasive wear make fatigue failure more probable in a machine or structural part?

11. The tread of a railway rail is subjected to gradual wear under the passage of rolling wheels, and occasionally to "brake burns" when the brakes are applied so rapidly that the wheels "slide." Which type of wear is most likely to start a fatigue crack which may fracture the rail? Why?

CHAPTER IX

THE PRODUCTION OF THE COMMON STRUCTURAL METALS: CAST METALS

Sources. The original sources of all our common structural metals are natural ores. These are generally *oxides* or sulfides of the metal, although there have been some instances of pure metal found in the natural state. The first step in the commercial production of a metal is the reduction of the ore or the removal of undesirable impurities. Very brief descriptions of the ores, the reduction processes, and the resulting metals, are presented in this book. For more detailed descriptions, references are listed at the end of the chapter.

IRON AND STEEL

Iron. The principal iron ores are iron oxides, such as hematite (Fe_2O_3), with some undesirable sulfur and phosphorus also present. Iron ore suitable for reduction to iron is found in large deposits in many parts of the world. The largest sources of iron ore in North America are in Alabama and in the Mesabi range at the west end of Lake Superior. The Mesabi range has been mined so long and so heavily that the higher-quality ores seem to be approaching exhaustion. Quite recently very promising deposits of iron ore have been found in eastern Canada, in eastern Quebec, and extending into Labrador. Extensive mining operations are in progress there.

The reduction of iron ore is carried out in a tall vertical stack lined with firebrick and called a *blast furnace*. Figure 47 shows in diagram a blast furnace. The ore, the fuel (coke), and a flux (usually limestone) are fed in successive layers into the furnace. The proportions are approximately one-sixth flux, one-third fuel, and one-half iron ore. The combustion of the coke takes place mainly at the bottom of the furnace in a blast of heated air and the coke burns to carbon monoxide, which is a powerful reducing agent. The ore is reduced to metallic iron which drips down to the bottom of the furnace. On its way down it absorbs some carbon and at the bottom is carburized iron with some impurities, especially sulfur and phosphorus. The product of the blast furnace is called *pig iron*. When the iron is to be shipped to distant steel works, or used for making cast iron, the product of the blast furnace is cast into pieces weighing about 100 lb. and called "pigs."

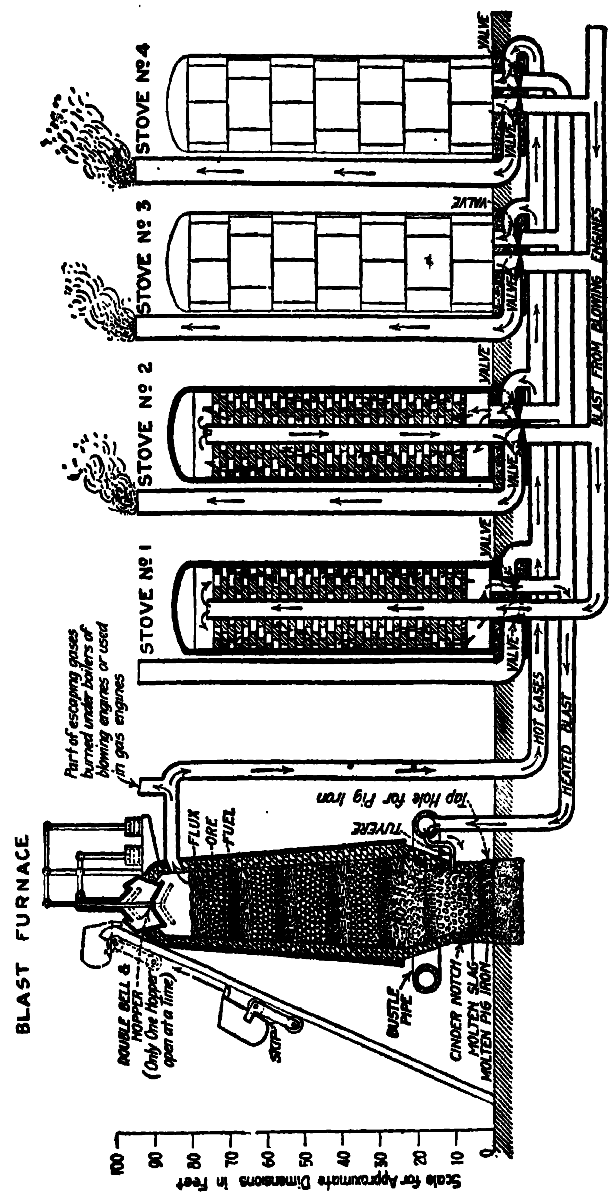


FIG. 47. Diagram of a blast furnace.

Refining of Pig Iron into Steel. General Features. Pig iron is a mixture of iron, combined carbon, carbon in the form of graphite flakes, and impurities of which sulfur and phosphorus are the most troublesome. To transform the pig iron into steel, the carbon content may be reduced by iron oxide (iron ore) which under heat forms a slag floating on top of the molten pig iron, or the molten pig iron may be decarburized by blowing air through the molten mass. It is difficult to stop the decarburizing process at the precise time when the desired carbon content has been reached, and it is usually the practice to decarburize the pig iron almost completely, and then to add carbon and with it manganese to the desired amount. Sometimes other desirable alloying elements are added. The resulting product is steel with the desired content of carbon, manganese, and perhaps other alloying elements, and very small percentages of sulfur and phosphorus.

In the refining process, the phosphorus in the pig iron tends to go into the slag, but if the slag has an acid reaction the phosphorus goes back into the steel again. However, if the slag is basic, most of the phosphorus remains in the slag. If limestone is added to the charge fed into the refining furnace, the reaction of the molten charge is basic and most of the phosphorus is removed. Steel made by a process using limestone to make the charge basic is known as *basic* steel, and steel in which the phosphorus is first removed by a basic process, and then the final refining is under acid conditions, is called *acid* steel.

Open-hearth Process of Steelmaking. The process most widely used in the United States for steelmaking is the open-hearth, sometimes called the Siemans-Martin, process. Figure 48 shows in diagram an open-hearth furnace. A shallow hearth *H* lined with refractory brick contains the charge, and above this hearth is a roof lined with firebrick. Fuel and air, preheated, are admitted through ports *P*. A chimney provides draft. The charge is fed through a charging door in the front of the furnace and the ingredients of the charge are pig iron, scrap steel, iron ore, and, for the basic process, calcined limestone. After the process is complete, the molten steel is tapped off through a taphole *T*. The air entering the furnace is preheated by passing it through passages *C* which are filled with a checkerwork of brick. Several such passages are used, and the alternate "regenerative" heating of air and fuel by hot bricks and the heating of the checkerwork of bricks by the waste gases of the furnace are similar to the process used for preheating the air blast in the blast furnace.

Control of the Open-hearth Furnace. The open-hearth furnace shown in Fig. 48 has a capacity of about 125 tons of steel per charge, and about 8 hr. are required to refine a charge. The progress of the refining

process may be told by tests of small samples of molten steel, taken at intervals and quickly cooled in a mold. Whether the process has proceeded far enough may be told fairly well by the appearance of the fracture of a cooled sample, or better by a rapid chemical or spectroscopic analysis of the steel in the sample. Usually, in the open-hearth process, in order to ensure the thorough removal of undesirable impurities, the refining process is carried so far that the carbon content of the steel becomes lower than that desired in the finished steel. This is remedied by adding carbon in some form, usually ferromanganese, and

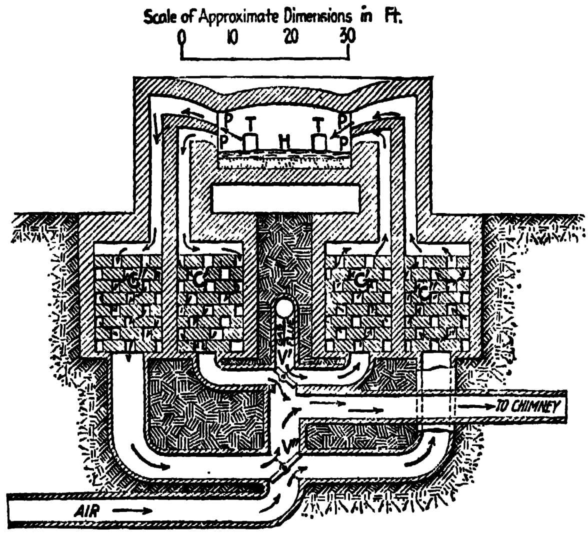


FIG. 48. Diagram of open-hearth steel furnace.

sometimes anthracite coal. This addition of carbon is called recarburization. In the acid process, recarburization is sometimes done in the furnace; but sometimes for acid steel, and nearly always for basic steel, it is carried out in the ladle into which the charge is tapped and from which the slag has been poured off.

Bessemer Process of Steelmaking. A considerable tonnage of steel is made by the bessemer process. This process does not produce as high a grade of steel as does the open-hearth process, but is somewhat less expensive. In the bessemer process, a blast of cold air is blown through molten pig iron, and the oxygen of the air burns out the carbon and most of the impurities of the pig iron. To this decarburized molten iron is added ferromanganese or other alloy rich in carbon and manganese to give the desired carbon and manganese content in the finished product.

Figure 49 shows, in diagram, a bessemer converter. The molten pig iron is first poured into this pear-shaped vessel, which is in a horizontal position. The bottom of the converter is pierced with small holes called tuyeres, and through these holes air is forced at a pressure of about 20 lb. per sq. in. The converter is tilted to a vertical position and the air blast turned on. Under the heat of the molten pig iron, the inrushing air burns out most of the impurities, increasing still further the heat of the molten metal. Silicon and manganese burn out first,

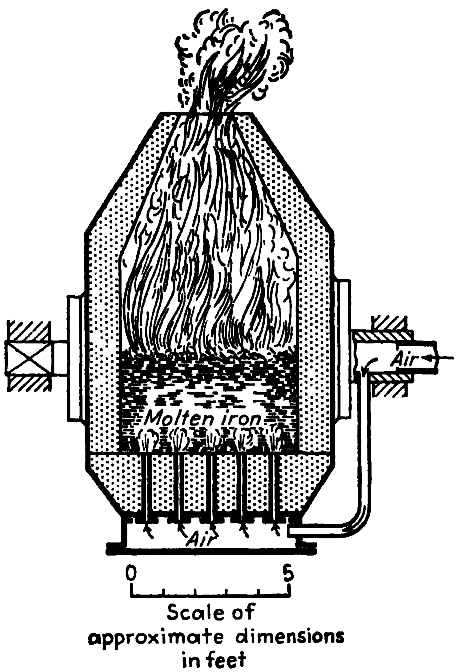


FIG. 49. Diagram of bessemer converter.

then carbon. If the burning out of impurities continues too long, there is danger that the iron itself will begin to oxidize. After the white flame of the burning carbon "drops," the contents of the converter are poured into a ladle and a small quantity of some alloy rich in carbon and manganese is added.

The manganese takes up some of the oxygen of the "burned" iron, and the final product is a steel of quite good strength and ductility. Its inferiority to open-hearth steel is largely due to the oxidation of the iron which is not completely remedied in this process.

Electric-furnace Steel. If the heat necessary to refine pig iron is produced by an electric current, the heat can be applied in direct contact

with the charge in the furnace and without contact of the charge with the outside air. Direct contact with the charge of a furnace means a more efficient heat transfer than is possible in the open-hearth or in the Bessemer process, in both of which there is contact of the finished product with air. Moreover, freedom from contact with air makes possible the highest refinement of steel without danger of oxidation.

For producing heat at low temperatures, electricity is usually much more expensive than burning fuel; however, for high temperatures, fuel becomes less efficient on account of the heat necessary to raise the temperature of the air which is blown in with the fuel. Electrically produced heat, on the other hand, increases in cost approximately proportionally to the temperature developed. At some limiting temperature, then, the cost of electric and of fuel heating will be the same, while above that limiting temperature the former may be actually the cheaper. Under conditions prevalent at many steel plants, the temperature used in refining steel approaches this limiting temperature, so that it becomes feasible to use electric furnaces for the making of high-grade steel.

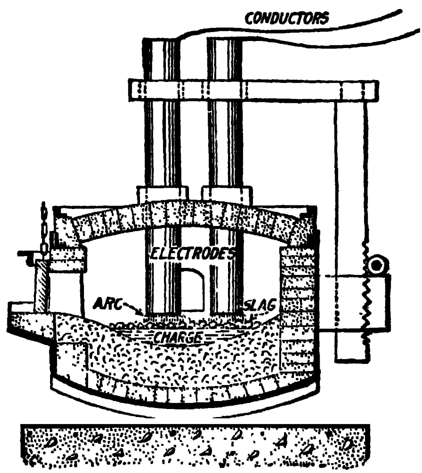


FIG. 50. Diagram of arc-type electric steel furnace.

Figure 50 shows a typical electric steel furnace in diagram. The heat is generated by an electric arc between a bath of unrefined metal and one or more electrodes which project through the roof of the furnace. The charge rests on the hearth and is purified by the reaction with the slag which is formed on top of the charge and which contains decarburizing, dephosphorizing and desulfurizing ingredients, as may be needed. After tests have shown that the refining process has proceeded far enough, the charge is drawn by tapping or by tilting the furnace.

The Finished Product of the Steel Furnace or Converter. If castings are to be made, the molten steel is poured into foundry molds. If the steel is to be rolled into bars, shapes, rails, or plates of sheet, the molten steel is poured into *ingot molds*. Figure 51 shows longitudinal sections of a typical ingot mold. After cooling in the ingot mold, the mold is "stripped" from the ingot, and the ingot is taken to the rolling mill for rolling into bars, shapes, etc. Steel ingots weigh from 1 to 20 tons, or even more.

Wrought Iron. Wrought iron is made by heating pig iron in a furnace which is bedded with rich iron oxide with a basic reaction. The oxide bed is melted and much of the silicon, manganese, sulfur, and phosphorus have been removed from the pig iron and have formed a molten slag. Then the temperature is reduced and there follows a combination of the carbon of the pig with the oxygen of the iron oxide, and carbon monoxide gas is formed, causing the charge to boil vigorously and much of the liquid slag to run out of a "slag door." The decarburized iron forms in pasty masses, which are removed from the furnace and removed to a squeezer or a hammer, where most of the liquid slag is squeezed out, and the balls are rolled into muck bars, which in turn are rolled into bars, plates, or shapes.

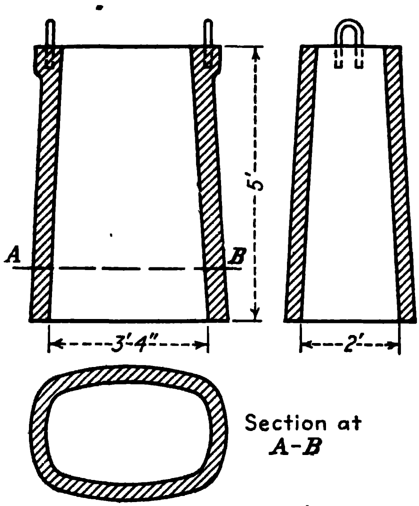


FIG. 51. Five-ton ingot mold.

Wrought iron has about the same strength and the same ductility as a good grade of soft steel. It is preferred by some blacksmiths who claim that it can be forged more easily than even soft steel. Wrought iron has been recommended by some engineers for water and gas pipes in the belief that it resists corrosion better than steel. On this point there are sharp differences of opinion among metallurgists. Some engineers prefer wrought iron for bolts and rods subjected to severe shock in the belief that it offers stronger resistance to shock than does mild steel. About this claim, also, there are differences of opinion among engineers.

NONFERROUS METALS

Copper. The ores of copper may be listed as native copper ores (Northern Michigan), oxide ores (South America and Africa), and sulfide ores, from which most of the copper is obtained today. In the United States there are large deposits of sulfide ores in the Rocky Mountain region. Copper is obtained from its sulfide ores by a complex process involving four stages: roasting, smelting, converting (bessemerizing), and electrolytic refining. Roasting partly burns out the sulfur of the sulfides, leaving oxides in their place. Smelting is carried out in a blast furnace or, more commonly, in a reverberatory furnace somewhat like that used for making wrought iron. In the smelting process the chief

changes are the removal of impurities in the slag and the production of a mixture of metallic sulfides of iron and copper. This mass is known as matte. The matte is further purified in a converter resembling a Bessemer converter. In the first stage of the conversion the air blown through the molten matte oxidizes the iron sulfide and the iron oxide formed passes into the slag. There is left "white metal" which is nearly pure copper sulfide. In the second stage of the conversion the copper sulfide is changed into crude copper, known as "blister" copper.

The final refining is by electrolysis in a sulfuric acid bath. Blister copper plates are used as anodes and plates of very pure copper as cathodes. The refined copper is cast into bars, cakes, slabs, and ingots.

Nickel. The most important ores of nickel are sulfide ores found in the province of Ontario, Canada. A complicated process of roasting, smelting in a reverberatory furnace to produce a matte of nickel, iron, and sulfur, "converting," grinding, leaching, and electrolysis is followed. After the electrolytic process the nickel cathodes are sheared or cast into various shapes for shipment. As a by-product of the refinement of nickel a considerable amount of copper is produced and a small but valuable amount of the precious metals, including platinum.

Zinc. Zinc ores are mined in seven or eight states of the Union and in Canada, as well as in seven or eight countries in Europe, Asia, Africa, and in Australia. The ores of zinc suitable for refining are mainly sulfides and carbonates. Two processes of producing the pure metal are in use: the distillation process and electrolysis. In both the first step is roasting, to convert the sulfides and carbonates into oxides. In the distillation process the oxide is then reduced by heating with carbon, after which the metal is vaporized and the vapor is led to condensing chambers where it is condensed to liquid form and cast into small ingots. In this form zinc is known as spelter. In the electrolytic process roasting is the first stage, after which the roasted material is leached with sulfuric acid and then deposited by electrolysis on aluminum cathodes from which the deposited zinc can be stripped. The anodes are lead. The sheets of zinc, stripped from the cathodes, are melted and cast into slabs.

Tin. Ores of tin in deposits large enough for commercial development are not found in North America. The principal deposits are found in the East Indies, in Central Africa, in Bolivia and in Cornwall, England. Tin ore is mainly tin oxide and the smelting process is a reduction by heating with carbon, followed by a secondary refining process, which may be either a refinement by heat-treating or by electrolysis. The refined tin is cast into slabs or pigs.

Lead. Large deposits of ores of lead are found in the United States and, although extensive deposits are found in Burma, Australia, Yugo-

slavia, and Canada, very little lead is imported into the United States.' The principal ore is a lead sulfide, from which the metal is obtained by roasting the ore to oxide and then reduction by heating with carbon in a blast furnace. The lead is then cast into pigs. When a very high degree of purity is necessary, an electrolytic method of refining is sometimes used.

Aluminum. All clayey earths contain aluminum, but only a few are suitable as commercial ores of aluminum. A hydroxide ore, bauxite, is the principal ore. It occurs in several European countries and in several states of the United States and Canada. The mineral cryolite, a fluoride of aluminum, is also important in the production of aluminum. The first stage in the production of aluminum is the preparation of alumina (aluminum oxide) from bauxite, followed by the electrolysis of this molten aluminum oxide protected by a slag of aluminum fluoride. The process is carried on in an electric furnace and requires a great deal of electric power; hence aluminum reduction plants are frequently located near water power.

Magnesium. Magnesium is the lightest of the structural metals. Some of the magnesium in the United States is produced from magnesium chlorides found in salt deposits and pumped to the surface as brine. Some magnesium is produced from sea water. The metal is produced by electrolysis in an electric furnace of molten magnesium chlorides with a small proportion of alkali chlorides. The metal collects at the surface of an iron cathode in the form of small globules, which coagulate and may be ladled out from time to time and cast into ingots.

Chromium. The ore chromite, an iron-chromium oxide, is the outstanding source of chromium and its alloys. A mixture of chromite with carbon is smelted in a furnace and an iron-carbon-chromium alloy is produced which is known as ferrochromium and which is the alloy used in producing alloy steels containing chromium. Small deposits of chromite have been found in the United States, but most of the chromite used comes from New Caledonia and Rhodesia.

Manganese. Manganese is used chiefly as an alloying ingredient in steel. All steel contains some manganese. Manganese is also used as an alloying element in some nonferrous metals. Several ores, oxides of manganese, are used and large deposits are found in the United States and Brazil, Gold Coast, India, South Africa, and Russia. From the ores an alloy, ferromanganese, is produced by smelting with coke, frequently in an electric furnace. Ferromanganese contains about 80 per cent of manganese with about 6 per cent of carbon.

Molybdenum. Molybdenum is used chiefly as an alloying element for steel and cast iron. Its commonest ore is molybdenite, which is a sulfide

of molybdenum. There are large deposits of this ore in the United States and also in Mexico and Norway. Molybdenite is smelted in an electric furnace with carbon as the reducing agent, yielding the alloy ferromolybdenum, which is the alloying agent in alloy steel containing molybdenum.

Vanadium. Vanadium is used chiefly as an alloying element for steel. Its ores are widely distributed, although rarely is any large deposit found in one location. A deposit in Peru is the most important today, but there are smaller deposits in Colorado and Utah, and in Portugal and South Australia. The alloy ferrovanadium, used in alloying steel, is produced by smelting in a crucible furnace with aluminum as a reducing agent, or in an electric furnace with silicon as a reducing agent.

Tungsten. The principal use of tungsten is for incandescent electric-lamp filaments. However, ferrotungsten is an alloy prepared by smelting from the ore wolframite, which is used in making high-quality tool steel. Ores of tungsten are found in the United States, but the largest deposits are in China and in Spain.

Cobalt. Cobalt is not found native, being mined with other metals. There are no important deposits of cobalt in the United States, but there are very large ones in Canada and in the Belgian Congo. The common ores of cobalt are sulfides of cobalt, or sulfides of cobalt and arsenic, or compounds of cobalt and arsenic. Cobalt is used as an alloying element in high-speed cutting tools of the cobalt-chromium-tungsten type, and as an alloying element for steels for permanent magnets and for high-temperature service.

Beryllium. Beryllium has rather recently come into prominence as a most effective hardening and strengthening alloying ingredient for copper. The principal ore of beryllium is the complex mineral beryl, which is the source of the beryllium oxide used in the production of the metal. Some deposits of beryllium ore have been found in the United States.

Titanium. This metal is obtained from oxide ores. Its weight per cubic inch is about 58 per cent of that of steel. Tensile tests of specimens from an annealed sheet of titanium showed somewhat higher values than the tensile strength of low-carbon steel, and the elongation was 25 per cent. Hardened titanium showed still higher tensile strength and 7.5 per cent elongation. The processing of titanium is still in the experimental stage, but it shows great promise as a strong lightweight metal.

Boron. This metal is obtained from the supplies of borax in the Southwestern deserts of the United States. It is a "promising" alloying element to replace part of the expensive nickel and chromium in alloy steels. It was under intensive study in 1952.

"Secondary" Metals and Alloying Ingredients. Today an appreciable percentage of the raw material for metals is derived from the scrap piles of metal-working or producing processes, and scrap metal such as worn-out rails, scrap wire, and scrap structural and machine parts. Especially useful is scrap metal containing alloying elements. The percentage of scrap metal used in steelmaking seems to be increasing. The numerous "scrap drives" of World War II furnish a vivid reminder of the potential importance of "secondary" (scrap) metals.

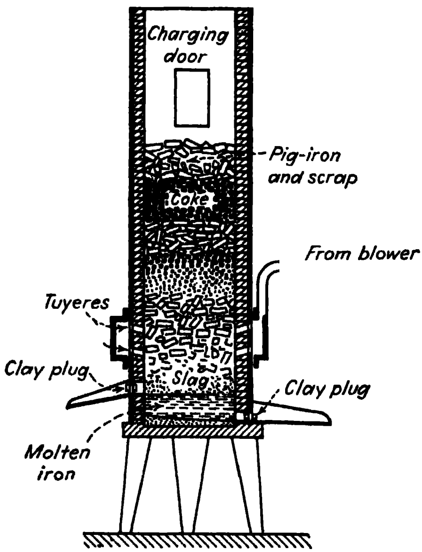


FIG. 52. Diagram of foundry cupo . for cast iron.

Cast Metal. Cast metal is run into molds while still molten and solidifies in the mold. In cast metal the growth of crystalline grains is not modified by rolling or forging and the restriction of the mold may cause severe internal stresses to be set up under uneven rates of cooling in different parts of the casting. Castings are less likely to be homogeneous in structure, and cast metal is usually weaker and less ductile than rolled or forged metal of the same chemical composition. The special case of castings made in metal molds under pressure (die castings) is considered later in this chapter. However, much improvement in strength and ductility of cast steel has been made in recent years.

Descriptions will be given of several procedures used in casting iron and steel. In general, with the exception of the cupola, similar methods are used for casting nonferrous metals as are used for ferrous metals.

Cast Iron; the Cupola. Pig iron mixed with scrap iron remelted and cast into molds is called *cast iron.* The remelting is usually done in a cupola which is somewhat like a small blast furnace. Figure 52 shows a diagram of a cupola. A blast of air under light pressure is blown through tuyeres at the bottom of a stack, which is charged from the top with alternate layers of coke (fuel) and pig iron mixed with scrap. The pig iron and the scrap melt and trickle down through the fuel to the bottom of the cupola, and a slag forms which floats on top of the melted iron. As in a blast furnace, the slag is drawn off through a tap hole and the iron through a tap hole a little lower in the

stack. The principal differences between the action of a blast furnace and that of a cupola are that in the latter no marked chemical changes take place, and the proportion of fuel to iron is much lower.

Graphite in Cast Iron. The characteristic feature of the structure of cast iron is the presence in the metal of flakes of graphite. Cast iron contains from 2.5 to 4 per cent of carbon, of which as much as nine-tenths may be in the form of graphite, the remainder being chemically combined with iron. Figure 53(*a*) is a micrograph of common "gray" cast iron, so called from the color of its fracture. The graphite has practically no tensile strength when it is in the form of thin flakes, and the flakes of graphite act like cracks, making the metal weak and brittle.

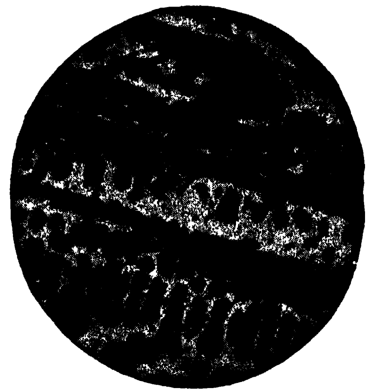
If molten cast iron is suddenly cooled, graphite flakes do not have time to form, and nearly all the carbon is chemically combined with the iron. Such cast iron is called white cast iron, and is strong, brittle, and so hard that it can be machined only by grinding. Figure 53(*b*) shows a micrograph of white cast iron. Localized sudden cooling of cast iron can be set up by lining a part of the mold with metal, which conducts the heat away from the iron, producing *chilled* iron. The rims of cast-iron car wheels are chilled to resist wear.

Malleable Cast Iron. This metal is produced from white cast iron by heating the chilled iron to about 1300°F. This causes the combined carbon to change to graphite, but graphite in the form of fine grains or nodules rather than in the form of flakes. This structure is shown in Fig. 53(*c*). Malleable cast iron is somewhat stronger in tension than is gray cast iron, and much more ductile, having about one-third the elongation of structural steel. Malleable cast iron is not as strong as cast steel but it can be poured at a lower temperature and it gives castings truer to pattern than ordinary steel castings. It is used for small castings of parts for which steel forgings would be too expensive and in which the metal should have a fair degree of ductility; for example, hubs of wagon wheels, small fittings for railway rolling stock, parts of agricultural machinery, pipe fittings, door hinges, etc.

Nodular Cast Iron. A limitation of the malleablizing process for cast iron is a tendency to poor malleablizing of thick sections. It has been found that treating molten cast iron with magnesium[1] causes the graphite to take a rounded nodular form [see Fig. 53(*d*)]. Nodular cast iron can be produced by the use of magnesium in thicker pieces than those which can be effectually malleablized by the simple annealing process. However, the strength and the ductility of nodular cast iron diminish somewhat as thickness of part increases. Nodular cast iron

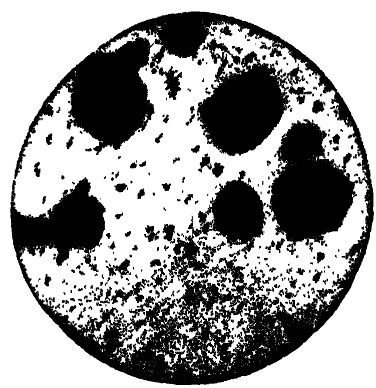
is a recent comer into the field of structural metals and gives promise of becoming very useful. In Tables VI(A) and VI(B), typical chemical compositions and strength, ductility, and hardness values for gray cast iron, malleable cast iron, and ductile nodular cast iron, are given.

(*a*) Gray cast iron unetched. Magnification 75 times. (*Micrograph made in Talbot Laboratory, University of Illinois.*)



(*b*) White cast iron. Magnification 100 times. (*Micrograph by F. E. Rowland.*)

(c) Malleable cast iron. Magnification 200 times. (*Courtesy of the National Malleable Castings Co.*)



(*d*) Nodular cast iron. Magnification 65 times. (*Micrograph by B. T. Chao and L. B. Vylstra.*)

FIG. 53. Graphite and combined carbon in cast iron.

Steel Castings. The molten steel from the furnace or the converter may be poured directly into molds to make steel castings. There are a large number of complex foundry problems involved in producing good steel castings. To ensure freedom from cavities formed during cooling it is usually necessary to pour the castings with large masses of steel, called sinkheads, so placed in the mold that molten steel may flow from

them to any part of the casting where there is a tendency toward the formation of cavities due to quick cooling (see Fig. 54).

The material of steel castings is not so strong or so tough as forged steel of the same chemical composition. As they come from molds steel castings usually have severe internal stresses set up in them by uneven cooling. These internal stresses may be greatly relieved, and the quality of the material in various parts of the casting made more nearly uniform, by annealing the finished casting, and this is very frequently done. For many purposes today steel castings are becoming available in place

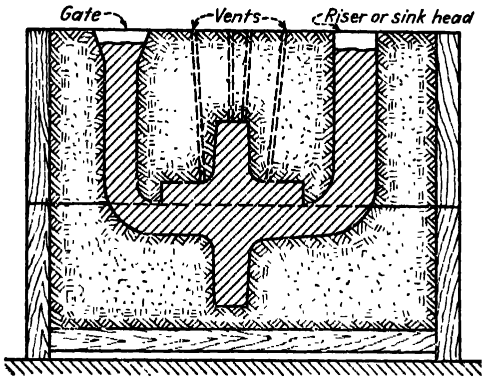


FIG. 54. Mold for steel casting.

of steel forgings on account of the greater ease of making castings of complicated shape, and steel castings are also displacing gray iron castings for many machine parts in which strength and toughness are prime requisites.

Nonferrous Metal Castings. The same general procedures are used in castings of nonferrous metals as in producing cast iron and cast steel. However, since the nonferrous metals are more expensive than the ferrous metals, more refined methods of casting can be employed. This is by the use of special synthetic sand for molds for aluminum and magnesium castings and in the occasional use of electric furnaces for melting nonferrous metals.

Centrifugal Castings. Ordinary castings are made by pouring molten metal into sand molds and allowing it to solidify there. For producing pipe, solid wheels, and disks with a central hole, centrifugal casting is in wide use. In centrifugal casting of pipe, a sand mold or a water-cooled metal mold is placed with its axis nearly horizontal, molten metal is poured in, and the mold is rotated. Centrifugal force causes the molten iron to assume the shape of a thin tube, and no core is necessary. The impurities, being lighter than iron, stay on the inside. The

thickness of wall is more nearly uniform than is the case with a cored casting, in which the core may "float" out of the center on the liquid iron. Centrifugally cast iron is somewhat stronger than ordinary gray cast iron.

Die Casting of Metals. The process of die casting consists in forcing molten metal into a metallic mold or die under a pressure of several hundred pounds per square inch. By this method, articles are produced accurate to a few thousandths of an inch in size, so that the machining necessary for finish is very much diminished and in many cases eliminated altogether. The metals most commonly used for die castings are aluminum base alloys, magnesium base alloys, and zinc base alloys. Typewriter parts, small pieces for airplane parts, and light machine parts are examples of articles quite commonly made by die casting.

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Questions

1. What is the chemical composition of the commonest iron ore?

2. Where are the principal deposits of American iron ore located?

3. Describe briefly the blast furnace and the general process of reducing iron ore to pig iron.

4. What is the fuel commonly used in the blast furnace, and what is the role of limestone in the reducing process?

5. What are the principal chemical changes which take place during the reduction of iron ore to pig iron?

6. What are the principal elements found in pig iron?

7. To produce 1,000 tons of pig iron, approximately how much iron ore is required (assuming 40 per cent iron in the ore)? How much fuel? How much limestone?

8. What are the general chemical changes involved in refining pig iron into steel?

9. Why must the contents of the furnace be recarburized before the product is a good grade of steel?

10. What is the difference between the basic process and the acid process in steelmaking? What kind of ore is necessary if the acid process is used?

11. Describe the open-hearth process of steelmaking.

12. Describe the recarburization process in the open-hearth furnace.

13. Name several fuels used in the open-hearth furnace.

14. What is the function of manganese in the process of refining pig iron into steel? (See Table XIV, page 141.)

15. Can the open hearth be used to produce the highest grades of steel? Give reasons for your answer.

16. Describe the bessemer process of steelmaking and its advantages and disadvantages, compared to the open-hearth process.

17. Describe the electric-furnace process of steelmaking. Why does it produce a higher grade of steel than either the open-hearth or the bessemer process?

18. Why is electric heating commercially feasible at high temperatures while it is not feasible at low temperatures?

19. What is the difference between wrought iron and low-carbon steel?

20. Describe briefly the processes used in refining copper ores and tell the general region where each ore is found.

21. Name the ores of nickel and tell where the principal deposits are located.

22. Name the principal ores and tell the location of the principal ore deposits of tin, lead, chromium, manganese, zinc, vanadium, tungsten, cobalt, beryllium, boron, and titanium.

23. What are the properties of titanium which make it a promising metal of the near future? What properties of boron?

24. In what ways is a foundry cupola like a blast furnace? In what ways different?

25. Define gray cast iron, white cast iron, malleable cast iron, nodular cast iron, and tell some structural or machine part for which each may be used.

26. Discuss the weakening of cast iron by the graphite in it.

27. Compare the tensile strength and elongation before fracture of white cast iron, gray cast iron, malleable cast iron, nodular cast iron, and structural plain carbon steel.

28. Name a structural or machine part which might be made out of nodular cast iron but not out of malleable cast iron.

29. Describe the process of centrifugal casting. What are its advantages? Name some structural or machine part besides pipe, disks, or wheels which might be made by centrifugal casting.

30. Which of the following parts do you think could profitably be made by a die-casting process: lamp posts, small-toothed gears, gas-turbine blades, machine frames, chains, adding-machine parts, bushings for bearings?

CHAPTER X

CRYSTALLINE STRUCTURE AND HEAT TREATMENT OF METALS: ALLOYING

Crystal Formation and Structure. All the common structural metals are crystalline when in the solid state. As a molten metal is allowed to cool, crystal formation occurs in a process quite similar to the phenomenon of crystals of ice forming as water freezes. The process of metallic formation may also take place when a part of the liquid molten metal is evaporated, since this evaporation may make the remaining liquid supersaturated, resulting in the precipitation of solid metallic crystals.

The relation between the crystal structure of a substance and its physical properties involves at least two factors, chemical composition and molecular or atomic arrangement. Both of these factors are important. A crystalline grain is a many-sided solid, normally bounded by plane faces and having a definitely oriented internal arrangement of the atoms or molecules. The outside form may be greatly distorted and deformed by interference with other crystalline grains, but the internal arrangement of the atoms and molecules is always orderly.

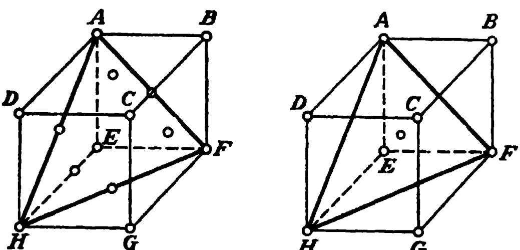
Space Lattice and X Rays. Interatomic forces in crystalline grains cause the atoms, or combination of atoms, to arrange themselves into definite groupings with respect to one another, and these unit groups (cells) repeat themselves in a regular geometric pattern. A large number of such unit groups make up a crystalline grain. The pattern or arrangement of atoms for any given metal is the *space-lattice* for that metal.

Atoms are very many times smaller than the smallest particle which can be detected by the electron microscope at its present state of development. By studying the reflection of X rays from crystals, the spacing and the arrangement of the atoms are determined.

Figure 55(*a*) shows a *face-centered space-lattice.* This is the one in which copper, lead, aluminum, and many of the noble metals crystallize. Figure 55(*b*) is a *body-centered space-lattice* and is the pattern which structural steel, iron, molybdenum, and tungsten take. Another type of space-lattice is that found in magnesium, zinc, cadmium, and chromium. This type is in the form of a hexagonal cylinder and is known as the *close-packed hexagonal lattice.*

Slip in a Crystalline Grain and Its Consequences. Slip under applied force in a crystalline grain takes place along or parallel to the planes in the crystalline grain in which the distance between atoms is least or, as usually stated, along the planes of greatest atomic density and in the direction of the rows of most closely spaced atoms. In the cubic space-lattice, planes of maximum atom density are AFH in the face-centered lattice and DBFH in the body-centered lattice (see Fig. 55). There are 12 possible slip planes in the body-centered and 48 in the body-centered lattice. In the close-packed hexagonal lattice (not shown) there are only three.

Probably the resistance of the crystalline grains in a structural or machine part to slip is the most important factor in determining the

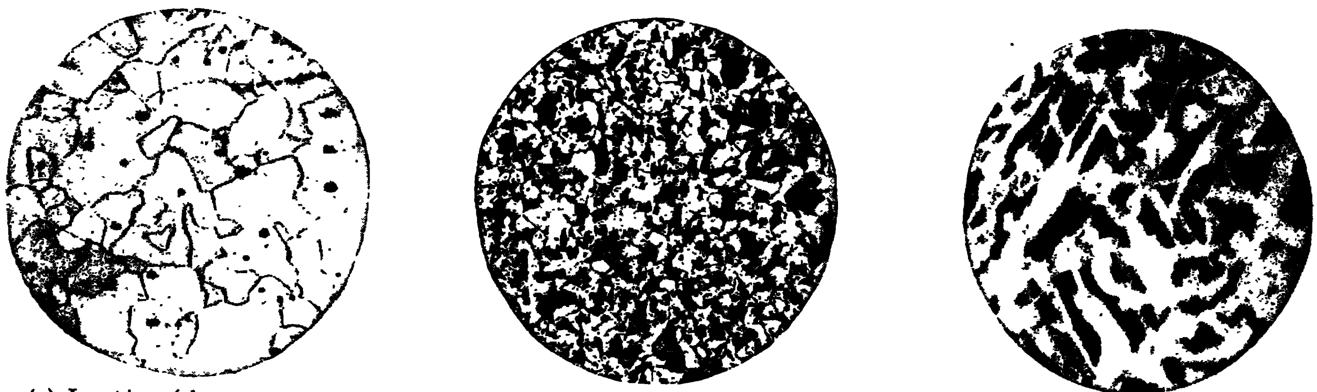


(a) Face centered (b) Body centered

FIG. 55. Slip planes in cubic space-lattices.

strength of the material and, perhaps, the strength of the whole part. However, appreciable structural damage to the part rarely if ever occurs until slip (or fracture following slip) has spread for an appreciable distance across crystalline grains. The interference placed in the way of spreading slip or fracture in crossing grain boundaries, and changing orientation to follow the slip planes in different grains, are factors in determining the strength of the material and of a structural or machine part made from it.

It may be said that when definite structural damage has occurred in a structural or machine part, there must have been slipping or cracking at the atomic level, at the microscopic level, and at the macroscopic (full-size) level, but that slipping, distortion, or even cracking *may* occur at the atomic level, the microscopic level, and even to a very small degree at the macroscopic level, without appreciable damage to the part. Slight permanent deformation, of a few hundredths of an inch at most, and small cracks which do not spread more than across a crystalline grain or two, do not *always* cause structural damage, but they are very definite danger signs. The strength of a structural part depends not only on the inherent strength of its crystalline grains, but on the obstructions



(*a*) Ingot iron (almost pure iron) as rolled. (*Courtesy of Prof. G. L. Clark, Department of Chemistry, University of Illinois.*)

(*b*) Structural steel as rolled. (*Micrograph in Metallogrpahic Laboratories, University of Illinois.*)

(*c*) Structural steel, suddenly quenched, showing large crystalline grains and sharp reentrant angles. (*Micrograph in Metallographic Laboratories, University of Illinois.*)

FIG. 56. Micrographs of ingot iron and structural steel showing crystalline structure. Magnification 100 times.

which are placed in the way of the spread of slip or fracture by such "road blocks" as grain boundaries, change or orientation of slip planes at each successive boundary reached, and occasional imperfections in the metal itself.[1]

We then see that evidence of a microscopic slip, or even of a microscopic crack, cannot be accepted as an undoubted evidence of structural damage in a machine or a structural member. The designer of such a member must, in most cases, rely on the results of careful physical tests of specimens of the material, on a computation of microscopic-scale stresses as determined by the formulas of machines of materials, and on an empirical factor of uncertainty, which is commonly called a factor of safety.

Figure 56 shows three characteristic micrographs of iron and steel. In Fig. 56(*a*) a micrograph of very nearly pure iron is shown. Figure 56(*b*) shows a micrograph of structural steel which has two types of crystalline grain, one of pure iron (light-colored grains), and the other of a combination of iron and carbide (dark-colored grains). Figure 56(*c*) shows a micrograph of structural steel in which there are large, long "dendritic" (treelike) crystals, which usually weaken the crystalline grain, and if such crystalline grains are common throughout a structural or machine part the whole part is weakened.

Alloys. In the preceding paragraph the presence of carbon in structural steel was mentioned. Common structural steel, then, is an *alloy* of carbon (about 0.20 per cent) and iron (about 99 per cent), together with small amounts of other elements [see Tables V(*a*), page 77, and X(*a*), page 87]. An alloy is a combination of two or more metals or metallic elements. In some cases the component elements may be soluble in each other in the molten state, as zinc and copper in brass, but the metals of which an alloy is made are not necessarily soluble in each other. The processes used in alloying metals have been developed to a remarkable degree, and the use of suitable alloying elements, and the subsequent heat-treatment to develop desired properties, at the same time avoiding the development of undesirable properties, constitute an important part of the science of metallurgy.

Heat-treatment. The freezing of molten metal containing two or more alloying elements is more complex than the freezing of a molten metal containing only one element. The different constituents may freeze at different temperatures and this may affect the freezing characteristics of all the constituent metals. Furthermore, if a cold solid alloy is heated only part way to the melting temperature of fusion,

[1] Such as graphite flakes in cast iron or flakes of oxide or sulfide in steel (see Figs. 12, 13, 20, 28, 53).

some of the constituents may be changed in character while still remaining solid. For example, in steel there may be a mixture of iron and iron carbide at room temperature, but when the steel is heated to some temperature above 1333°F. this mixture will change to a solid solution of carbon dissolved in iron.

In general, heat-treatment of a metal involves two or more of the following processes:

1. Heating the metal to some predetermined temperature at which one or more of the constituents will change character in the solid state.

2. Cooling the heated metal at a controlled rate by quenching in a liquid or by cooling in air.

3. After cooling to some definite temperature in step 2, reheating to a somewhat lower temperature than that reached in step 1.

4. Final cooling to room temperature, usually by cooling in air, but sometimes by quenching in oil or even water.

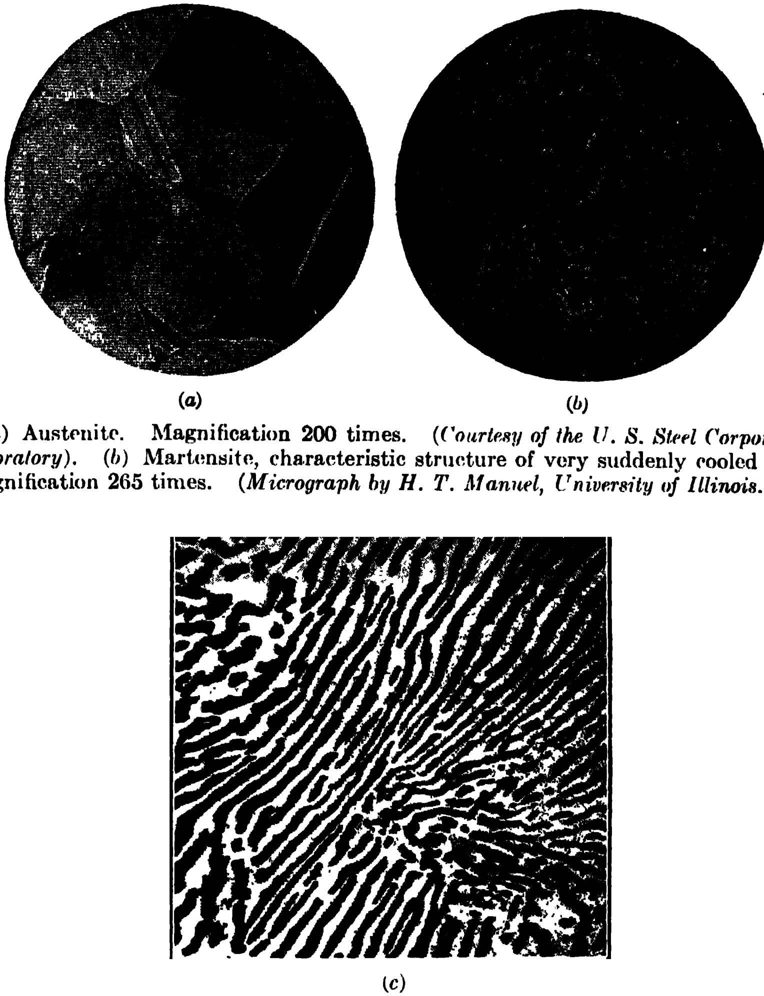
Heat-treatment of Carbon Steel. At room temperature, nearly all the carbon in steel is ordinarily in microscopic crystals of iron carbide, Fe_3C, known as *cementite.* At temperatures well above 1333°F. (such as 1700°F., for example), the cementite decomposes and the steel becomes a solid solution of carbon in iron, known as *austenite.* Austenite is strong, not very hard, nonmagnetic, and has a face-centered cubic space lattice.

If the hot austenitic steel is cooled very rapidly by quenching in a cold liquid (cold water or brine, for instance), the steel is changed to a mass of needlelike crystals. This state is known as *martensite* [Figure 57(*b*)]. These crystals consist of a semi-stable solid solution of carbon in iron which differs from austenite by having a body-centered tetragonal space lattice. Martensite is very strong, hard, brittle, and magnetic. It will remain stable only at fairly low temperatures, breaking down when subjected to temperatures as low as 350°F. for long periods.

Martensite is too brittle for most engineering applications, so it is usually "tempered" by reheating to some temperature between 350°F. and 1200°F. and cooling again (steps 3 and 4 above). The final tempered product is a mixture of iron and cementite crystals, and is more ductile than martensite, softer, and not as strong. The amount of decrease in strength is a function of the tempering temperature and soaking time.

If the hot austenitic steel is cooled off slowly instead of being quenched, it changes to a mixture of iron and *pearlite.* Pearlite is itself a mixture of very thin layers of iron and cementite. Figure 57(*c*) shows the structure of laminated pearlite.

This discussion of the heat-treatment of steel indicates some of the basic elements of heat treating. In order to produce special combinations of strength, hardness, and ductility, more complicated processes are frequently necessary (see references 5 and 7 at the end of this chapter).



(*a*) Austenite. Magnification 200 times. (*Courtesy of the U. S. Steel Corporation Laboratory*). (*b*) Martensite, characteristic structure of very suddenly cooled steel. Magnification 265 times. (*Micrograph by H. T. Manuel, University of Illinois.*)

(*c*) Pearlite. Magnification about 2,000 times. (*Micrograph by R. E. Cramer, University of Illinois.*)

FIG. 57. Structure of steel at different stages of transformation from solid solution (austenite) to mechanical mixture (pearlite).

Cold-working, Residual Stresses, and Normalizing. When an unheated structural or machine part is subjected to heavy rolling, pressing, drawing, cold-hammering or "peening" by a shower of hardened shot, the crystalline grains, especially near the surface, are somewhat distorted. This distortion is called cold-working and, unless the cold-working is so severe as to cause incipient cracks in the metal, the yield strength of the metal is usually considerably increased, the tensile

strength somewhat increased, the fatigue strength sometimes increased, but the ductility decreased. This cold-working sets up residual stresses in various sections of the part, and appreciable distortion of the part is not infrequent. The residual stresses and the distortion may be nearly all removed by *annealing* or may be lessened very appreciably by "normalizing," which is similar to annealing, except that the cooling is more rapid, sometimes taking place in a stream of air, rather than in still air.

Quenching Stresses. As a steel member is cooled rapidly from a high temperature, if the rate of cooling is not uniform throughout the member, high internal stresses may be set up. These stresses may cause failure directly and, if they do not do this, they may add to the stresses imposed on the member by service load, with a resulting service failure due to the combined stresses. Of course in some cases the cooling stresses and the stresses due to load may *oppose* each other, but it is hardly wise to count on such a stress-relieving action.

"Burned" Steel. Most of the heat-treatments used for steel involve heating the metal up to a high temperature, sometimes as high as 1800°F. The temperature should not be allowed to go above that specified for the steel, since overheatings may result in large crystalline grains and lowered strength. Furthermore, if the steel is heated close to the melting temperature, oxidation and localized melting may take place within the grain boundaries. If this occurs, the steel is said to have been "burned" and is unfit for use. Table XIII shows the effect of some typical heat-treatments for steels.

Heat-treating of Nonferrous Metals. Heat-treatment is not as widely used for improving strength or ductility of nonferrous metals as it is with ferrous metals. Cold-rolling, cold-drawing, shot-peening, and other "cold-work" treatments seem to be more effective for most nonferrous metals than are heat-treatments. Heat-treatments of nonferrous metals are sometimes used to relieve residual stresses.

A few nonferrous metals can be effectively hardened by heat-treatment. Aluminum-copper and aluminum-zinc are two such alloys, and alloys of copper and beryllium are very markedly hardened by a suitable heat-treatment. The heat-treatment for nonferrous metals is usually a duplex process in which the first stage is a short-time heating, followed by a quench, usually in water. Then follows a long-time treatment at a considerably lower temperature than that used in the first phase. This second phase is sometimes called "aging," sometimes "precipitation hardening," because under the "aging" the crystalline grains precipitate hard particles which strengthen the metal. Some of the "aging" processes are patented.

TABLE XIII. TYPICAL HEAT-TREATMENT AND STRENGTH AND DUCTILITY PROPERTIES OF VARIOUS STEELS

Data from the records of the Talbot Materials Testing Laboratory, University of Illinois

Metal	Heat-treatment	Yield strength, lb. per sq. in.	Tensile strength, lb. per sq. in.	Elongation in 2 in., per cent	Endurance limit, lb. per sq. in.[1]
Armco iron (0.02% carbon)..........	Annealed	19,000	42,400	48.3	26,000
Armco iron (0.02% carbon)	Heated to 1500°F., quenched in water	36,000	50,000	36.3	33,000
0.37% plain carbon steel	Normalized, heated to 1495°F., cooled in still air	34,900	71,900	29.4	33,000
0.37% plain carbon steel	Heated to 1550°F., quenched in water, reheated to 1050°F., cooled in air	87,300	102,600	23.3	57,000
0.52% plain carbon steel	Normalized, heated to 1550°F., cooled in air	47,600	98.000	24 4	42,000
0.52% plain carbon steel	Heated to 1450°F., quenched in water, reheated to 1200°F., cooled in air	84,300	111,400	21.9	55,000
1.20% plain carbon steel	Normalized by heating to 1580°F. and cooling in still air	60,700	116,900	7.9	50,000
1.20% plain carbon steel	After annealing, heated to 1625°F, and quenched in oil	140,000	220,000	0.8	105,000
3.50% nickel steel (0.41% carbon)	Heated to 1525°F., cooled in furnace, reheated to 1525°F., quenched in oil, cooled in furnace	108,700	123,300	22.5	64,000
Chrome-nickel steel (0.24% carbon)	Heated to 1525°F., cooled in furnace, reheated to 1525°F., quenched in oil, reheated to 700°F., cooled in furnace	128,100	138,700	18 2	68,000
Stainless steel, approx. 18% chromium, 8% nickel (0.33% carbon)	Annealed by heating to 1725°F and cooling in furnace	65,000[2]	115,900	25.3	55,000

[1] Endurance limit under reversed bending.
[2] Estimated from reported "proportional limit."
Note: The above heat treatments were all made on rather small pieces of metal, mostly on rods not over 1 in. in diameter. The plain carbon steels would not show such high values if the treatments had been made on larger pieces.

ALLOYING OF THE FERROUS METALS

Beneficial Effects of Alloys. Table XIV lists the specific effects of various alloying elements in steel. In addition to the strengthening effect of an alloy, a cleansing effect known as "scavenging" is caused by some alloying elements, notably aluminum and vanadium. Scavenging alloying elements absorb gases or facilitate their escape from molten metal, combine with undesirable elements (*e.g.*, sulfur) to form harmless compounds, or tend to prevent oxidation of iron.

A second beneficial effect of some alloying elements for steel is the slowing up of the rate of change of crystalline structure of steel during cooling. If a large bar of plain carbon steel is heated and quenched, the hardening effect does not penetrate to the central core of the bar because the effect of the quenching does reach the central core before that core has become quite well annealed. Alloying elements tend to slow up this annealing process and to allow the effect of the quenching to reach the central core before annealing has occurred to any great extent.

A third beneficial effect of some alloying elements for steel, especially of chromium, is the increased resistance to corrosion. A combination of 18 per cent of chromium with 8 per cent of nickel together with from 0.07 to 0.16 per cent of carbon makes an effective "stainless" steel. It is tough and ductile while cold and can be used under temperatures up to 1000°F. and stresses up to about 10,000 lb. per sq. in.

Alloy Steels. Common alloying elements and the lowest content at which they produce appreciable effect on steel are as follows:

	Per cent
Manganese	1.00
Silicon	0.30
Nickel	0.50
Chromium	0.50
Molybdenum	0.25
Tungsten	1.00
Vanadium	0.15
Aluminum	0.50

Injurious Effects of Certain Impurities in Ferrous Metals. *Phosphorus.* Phosphorus in steel comes from phosphates in the ore and flux used in making steel. Phosphorus tends to make steel "cold-short" (brittle at low temperatures). In rail steel phosphorus is regarded as an especially undesirable ingredient, since rails are subjected to occasional heavy shocks at winter temperatures. Phosphorus, while somewhat diminishing the ductility of steel, increases its strength. Some of the "low-alloy" steels (see page 77) use phosphorus as a strengthening ingre-

TABLE XIV. EFFECT OF ALLOYING ELEMENTS IN STEEL
Based on article by R. H. Aborn in *Iron Age*, March 5, 1925

Alloying element	General influence	Definite effect	Uses and beneficial effects	Disadvantages
Aluminum (Al)	Deoxidizes	"Quiets" molten steel, facilitates escape of gases	Up to content of 0.05 per cent standard remover of gases	Excess of Al tends to cause formation of graphite
Chromium (Cr)	Forms a very stable carbide	Gives great hardness; makes quenching effective to considerable depth	Cutting tools, ball bearings, rolls. A content of 13–18 per cent Cr gives stainless iron and steel, and steels serviceable at high temperatures. With Ni, Cr is used for general purpose alloy steels. Adds hardness and strength	With certain heat treatments danger of brittle steel
Manganese (Mn)	Gives fine-grained crystalline structure. Deoxidizes, desulphurizes	Removes oxygen and sulphur from steel. A content of 10–12 per cent Mn gives an "Austenitic" amorphous structure with great resistance to wear	Up to 2 per cent Mn as deoxidizer and desulphurizer, and to increase strength 10–12 per cent Mn for crusher jaws and other mining and milling equipment, safes, frogs, switches, special rails	Steel with high Mn content extremely difficult to machine
Molybdenum (Mo)	Similar to Cr and Ni	Next to carbon the most effective hardening element	General purpose alloy steels (with Ni, Cr or V). Allows effective control of heat treatment	Expensive, variable quality, volatilizes from surface layers on rolling. Tendency to seams and brittleness
Nickel (Ni)	Gives fine-grained crystalline structure	Up to 4 per cent increases strength with little loss of ductility. Makes quenching effective to greater depths than in plain carbon steel	General purpose alloy steels. Makes possible heat treatment of fairly large pieces. Adds strength with little loss of ductility	Scale formed in rolling; rough surface
Silicon (Si)	Deoxidizes. Coarsens crystalline grain	Up to 1.75 per cent Si elastic strength is increased with little loss of ductility	Structural steel, spring steel (with Mn), standard deoxidizer	Silico-manganese spring steel lacking in toughness
Tungsten (W)	Forms extremely stable carbide. Gives fine-grained crystalline structure	Increased strength accompanied by brittleness. Quenching effect not so deep as for Cr	Cutting tools, permanent magnets. Allows very effective control of heat treatment	Brittleness of tungsten steel unfits it for use as structural steel
Vanadium (V)	Deoxidizer. Gives fine-grained crystalline structure	Deoxidizing and hardening agent. Gives high elastic and tensile strength	Spring steel and fine alloy steel (with Cr). Forms fluid slag giving "clean" metal. Checks grain growth	Expensive

At the present time the possibilities of *boron* as an alloying element for steel are being studied in many laboratories. A small percentage of boron seems to have a large effect in increasing the hardness of steel.

dient. How high a phosphorus content is necessary to cause steel to be dangerously brittle in service is still an unsettled question. For most purposes the phosphorus content of steel is limited to 0.05 per cent, except for thin-rolled low-carbon plates in which case a fairly high phosphorus content makes hot rolling easier.

Sulfur. Sulfur in iron or steel comes largely from the coke used in the blast furnace. The effect of sulfur is a tendency for steel to be "hot-short," *i.e.*, brittle at a red heat. Sulfur is an ingredient more troublesome to the steel maker than to the steel user; since if it is possible to roll the steel with a smooth surface, there is rarely sufficient sulfur present to injure the service qualities of the metal. A high sulfur content tends to make steel cut smoothly in a machine tool, and specifications for screw stock usually require a high sulfur content.

Iron Oxide; "Dirty" Steel. Iron oxide in steel comes from the use of rusty scrap in the converter or the open-hearth furnace, or from the air blown through the converter or the furnace, especially during the last moments of the refining process, particularly the bessemer process. Iron oxide in steel is usually present in the form of microscopic nodules or "inclusions," or sometimes in "slag streaks," and steel with many such inclusions is known as "dirty" steel. The effect of oxide inclusions in steel is to form microscopic regions of high localized stress and to render the steel of somewhat uncertain strength, especially under repeated stress.

It has not been found feasible to formulate quantitative requirements for freedom of steel from dirt, but steel is judged as clean or dirty, from its appearance under the microscope.

Other Injurious Ingredients. Freshly produced (ionized) hydrogen may make steel extremely brittle, as is illustrated in the process of pickling steel in sulfuric acid to remove scale. The hydrogen gradually works out of the steel and the brittleness disappears. The hydrogen may be removed by heating for a few hours at a temperature of a few hundred degrees Fahrenheit. A stream of hydrogen gas does not produce this embrittling effect, unless continued for a long time at a high temperature. Hydrogen entrapped in hot steel, and prevented from escaping by the cooling and stiffening of the outer layers, may build up very high pressures over microscopic areas—pressures high enough to cause microscopic cracks in steel.

Nitrogen makes steel hard and brittle. It may be an injurious element in ordinary steel, but is used to give steel a very thin, hard coating in the nitriding process (see page 157).

Decarburized Steel. During the fabrication and heat-treating of high-carbon and medium-carbon steel, the outer surface is sometimes attacked by air, or by iron oxides, causing the oxidation of some of the

carbon in the surface zone, with a consequent lowering of the carbon content at the surface and a reduction of strength of the steel at the surface where it has to withstand the maximum bending and twisting stresses and, consequently, where it can least afford any loss of strength.

FIG. 58. Longitudinal section of the head of a railroad rail, showing decarburized surface. The grains of ferrite in the surface zone of the rail head indicate that the steel has been changed from a steel with about 0.72 per cent of carbon to one with about 0.20 per cent of carbon. Below the decarburized zone the carbon content of the steel is still about 0.72 per cent. At the top of the micrograph can be seen particles of scale which were loosened in polishing. Magnification 125 times. (*Micrograph by R. E. Cramer.*)

Decarburization is a rather common cause of structural damage to large shafts and axles that are subjected to repeated stress. A fatigue crack frequently starts in a weak decarburized location on the surface and spreads until fracture occurs or the crack is detected. Figure 58 is a micrograph showing a decarburized layer in rail steel.

Decarburization may be minimized by control of furnace atmosphere. A decarburized part of the surface of a steel member can be strengthened

by localized heat-treatment, by cold-rolling, or by shot-peening (see Chap. XI).

Low-carbon steels are useful in welded construction for which special heat-treatment is rarely available; hence the importance of their high strength in the "as rolled" condition.

"Stainless" Iron and Steel. Structural steel with a copper content of 0.2 per cent is more resistant to atmospheric corrosion than structural steel with no appreciable copper content. Chromium is the most effective ingredient for making steel or iron resistant to corrosion and to heat, and it is especially effective if the chromium content is 16 per cent or more. The protection against corrosion is due to the dense tough film of oxide formed over the surface of the metal. Steel or iron with a chromium content of 16 per cent or greater is classed as "stainless."

The numerous brands of stainless steel on the market may be divided into three groups. The steels in the first group have a chromium content lower than 16 per cent and a carbon content lower than 0.4 per cent. They respond to heat-treatment and are not excessively brittle. They may be machined by the use of specially designed cutting tools. They can be welded. They are satisfactory for resisting weather and water and can be used at temperatures up to 1500°F.

The steels in the second group have a chromium content higher than 16 per cent and a carbon content not over 0.4 per cent. They do not respond readily to heat-treatment and are brittle, especially at notches. They can be forged, rolled, or cold-drawn, and can be machined by the use of specially designed tools. They can be welded, but some metals in this group are very brittle near a weld. They are superior to the steels in the first group in resistance to corrosion, and such of them as do not show grain growth at high temperatures are superior to the steels in the first group in resisting temperatures above 800°F.

The stainless steels in the third group contain sufficient chromium to make them nonmagnetic and "austenitic." They do not respond readily to heat treatment. They are very tough. They can be forged, rolled, or cold-drawn but can be machined only with great difficulty. They can be welded. Above 16 per cent chromium their resistance to corrosion is excellent. The metals of this group are better even than the metals of the second group for service under temperatures above 1000°F.[1]

"18-8" Steel. A stainless steel in common use today is known as "18-8" steel because it contains approximately 18 per cent of chromium and 8 per cent of nickel. Its carbon content ranges from 0.07 to 0.16 per cent. It is remarkably tough and ductile when cold. It cannot

[1] Paragraphs based on article by Frank R. Palmer in *Iron Age*, Mar. 15, 1928.

be hardened by heat-treating, but severe cold-working can increase its Brinell hardness from 140 to nearly 400. It is an "austenitic" steel, shows remarkable freedom from grain growth and creep at high temperatures, seems to fall between the second and third classes noted in the preceding paragraphs, and can be used up to 1000°F.

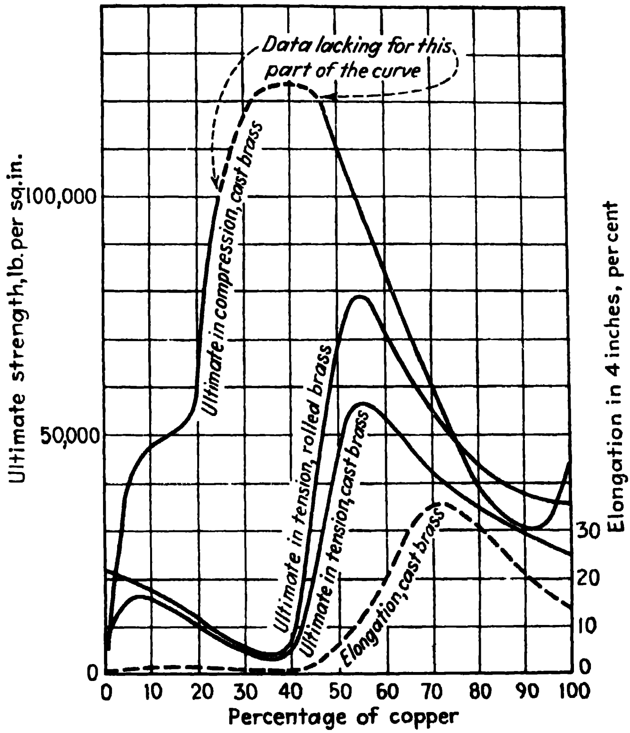


FIG. 59. Properties of copper-zinc alloys (brasses). The modulus of elasticity for brasses varies from 9,000,000 to 14,000,000 lb. per sq. in., averaging about 13,000,000 lb. per sq. in.

ALLOYING OF NONFERROUS METALS

Comparison with Alloying of Ferrous Metals. The general principles of strengthening by the solid solution of an alloying element and of the formation of hard alloy particles hold for nonferrous metals as for ferrous metals. The most marked difference is the absence of carbon as an alloying element in the nonferrous metals.

Copper-Zinc Alloys; Brasses. Copper and zinc alloyed constitute brass, one of the commonest of alloys. Copper and zinc can be alloyed in any proportion, but not more than 40 per cent of copper is used in the common commercial copper-zinc alloys. The average mechanical

properties of brass with varying percentages of copper and of zinc are shown in Fig. 59.

Brass can be cast directly into shape and rolled or drawn into sheets, tubes, rods, and wire. It resists corrosion better than iron or steel and finds a wide use for hydraulic fittings and pump linings and in places where prolonged exposure to moisture is necessary. Brass costs seven

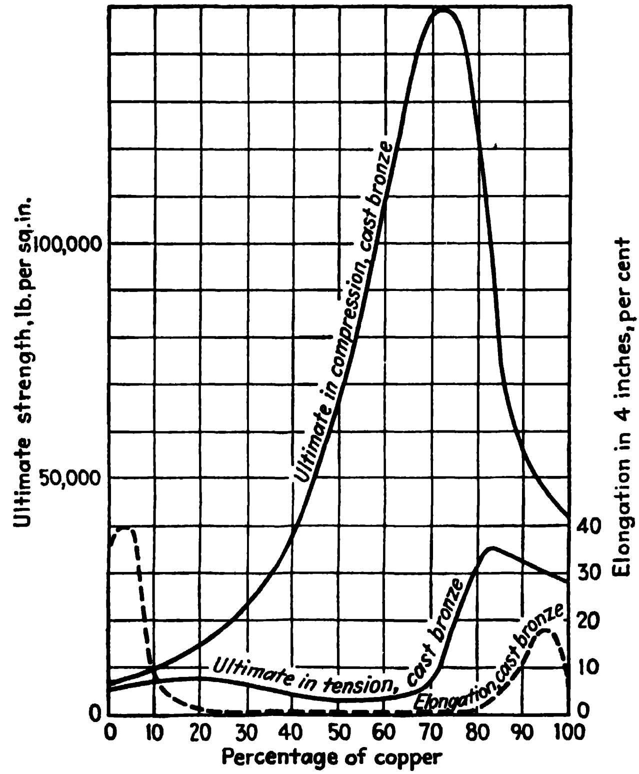


FIG. 60. Properties of copper-tin alloys (bronzes). The modulus of elasticity for bronze varies from 9,000,000 to 17,000,000 lb. per sq. in., averaging about 15,500,000 lb. per sq. in.

or eight times as much as mild steel. Brass is also a useful metal for bearings. If it is attempted to run a steel shaft in a steel bearing, the rubbing surfaces cut and tear each other. If, however, a softer metal, such as brass, is used as a bearing metal against steel, a smooth surface is worn and, with light lubrication, cutting and tearing is not as likely to take place.

Copper-tin Alloys; Bronzes. Copper and tin also can be alloyed in any proportion. The properties of bronze, as copper-tin alloys are called, for varying proportions of copper are shown in Fig. 60.

Bronze can be cast into shape or rolled into wire, rods, and sheets. It resists corrosion even better than brass and is a more expensive alloy than brass. Its uses are, in general, the same. The terms brass and bronze are somewhat loosely used in practice, either term being frequently used to denote any yellow metal containing copper in large proportion.

Copper-nickel Alloys; Monel Metal. Various alloys of copper and nickel are in use today. They have a fairly high resistance to ordinary corrosion and are machinable. Probably the best known of these alloys is monel metal containing about 68 per cent nickel, 28 per cent copper, and a little manganese and iron. Monel metal is smelted from an ore containing copper and nickel in approximately the desired proportions, without separating the two elements.

Monel metal is available in the commercial forms of rods, sheets, wire, and welded tubing. It is produced both hot- and cold-worked. It is very widely used for structural and machine parts which must have a very high resistance to corrosion and which demand a metal of high strength.

Copper-beryllium Alloys. An alloy of copper and beryllium is available in the form of sheets, wire rods, and tubes. It possesses the property of being strengthened by cold-working[1] like other copper alloys and is capable of being strengthened and hardened by heat-treatment to an extent greater than that of any other copper alloy known today. Copper-beryllium is especially promising as a strong metal for nonmagnetic springs for instruments.

Aluminum-copper Alloys. Several alloys of aluminum containing 5 per cent or less of copper, with a small amount of magnesium, are in common use as a structural metal. Their weight averages about 0.1 lb. per cu. in., about one-third the weight of structural steel. The static strength of these aluminum-copper alloys is about the same as that of structural steel. The strength of aluminum-copper alloys under repeated stress is lower than that of structural steel. The term "duralumin" is sometimes used to designate aluminum-copper alloys.

Aluminum-zinc Alloys. Several aluminum-zinc alloys are now available. A common alloy contains about 6 per cent of zinc with small quantities of copper and magnesium. The strength of the aluminum-zinc alloys is greater than that of the aluminum-copper alloys on the market, but the ductility is lower. The strength under repeated stress is greater than for the common aluminum-copper alloys, but the ratio of fatigue strength to static tensile strength is lower than that for structural steel. Values for chemical content for a typical aluminum-zinc alloy

[1] The subject of cold-working of metals is discussed more fully in Chap. XI.

are given in Table VII(*a*) and values for strength and ductility are given in Table VII(*b*).

Aluminum-clad Alloys. Since pure aluminum is more resistant to moist atmospheric corrosion than the structural alloys of aluminum, a coating of pure aluminum would be beneficial for alloys to be used in contact with moisture and air. Such a coating is provided for Alclad sheet and plate material by rolling a "sandwich" of aluminum alloy between two thin sheets of pure aluminum. This lowers the strength of the surface layer below that of the alloyed metal, and this lowers the static strength slightly and the fatigue strength considerably, since a crack may start in the relatively weak pure aluminum coating under rather low stress and spread through the alloyed metal.

Magnesium Alloys. The principal alloying element used with a magnesium base is aluminum. Usually a fraction of 1 per cent of manganese is present in a magnesium-aluminum alloy; sometimes a little zinc. In general the magnesium alloys are lighter and not quite so strong as the aluminum alloys; they weigh approximately 0.063 lb. per cu. in. Typical chemical analyses are given in Table VII(*a*), typical strength and ductility properties are given in Table VII(*b*).

Nickel-chromium Alloys. Some alloys made up principally of nickel and chromium show extremely high resistance to corrosion and stand up remarkably well under temperatures which would cause iron or steel to fail quickly by creep (or flow). Most of them contain from 60 to 80 per cent of nickel, 10 to 20 per cent of chromium, and small quantities of iron and manganese. The tensile strength at ordinary room temperatures covers the range of strength of structural steel. These alloys are used widely for heating elements in electric furnaces and for furnace muffles, carburizing boxes, annealing boxes, and tubes and other equipment exposed to high temperature. Their great resistance to oxidation and their relatively great strength at high temperature make possible the use of thin-walled boxes and tubes, which means less loss of heat in the walls.

Special Alloys. Space is lacking to enumerate all the alloys of metals in common use. A few alloys of special significance will be briefly noted.

Aluminum bronze is an alloy of aluminum with copper. The aluminum gives the alloy lightness, while the addition of copper to pure aluminum increases its strength.

Manganese bronze is an alloy of copper with manganese and a little iron. The manganese by its strong affinity for oxygen "cleanses" the metal of any small particle of oxide. Manganese bronze has a very high strength, about equal to that of structural steel. Manganese bronze resists corrosion by either salt or fresh water remarkably well and is used for propeller wheels and other parts of ships.

Phosphor bronze is prepared by the addition of a little phosphorus to a copper-tin alloy. The phosphorus itself has but little effect on the physical properties of the bronze, but it unites with any oxide present and "cleanses" the alloy from the injurious effects of the oxide.

Alloys for Die Casting. The process of die casting consists of forcing molten metal under pressure into a metallic mold or die. In this way castings can be produced so close to desired dimensions that machining is unnecessary. Small gears, typewriter parts, and other light machine parts are now produced in great numbers by die casting. Three types of alloy are in common use: (1) aluminum-base alloys, (2) zinc-base alloys, and (3) magnesium-base alloys.

Physical properties of characteristic die-casting metals are given in Table VII(b).

Bearing Metals. In choosing metals for bearing surfaces where shafts turn in bearings or members slide on one another, it is of prime importance that the bearing metals should have sufficient compressive strength to carry the bearing pressure, should wear to smooth surfaces as they rub together, and should develop a minimum of friction when they actually come in contact, as, for example, when a shaft is starting or stopping. All satisfactory bearing metals have a characteristic crystalline structure made up of hard crystals alternating with relatively soft crystals. The hard crystals support the load and resist wear; the softer crystals suffer some plastic deformation and permit the hard crystals to adjust themselves to the surface requirements of the rotating shaft or the sliding member. Moreover, the softer crystals wear slightly below the surface of the harder crystals and thus form minute depressions on the surface which retain lubricant. This retained lubricant is sufficient to keep the bearing from undue friction and heating when starting or stopping. Around a properly lubricated shaft in motion is a film of lubricant, so that the nature of the bearing metal is not of much consequence once the shaft is up to speed, but the lubricant-retaining nature of good bearing metal is of great consequence during starting and stopping. Usually it is found advisable to make the shaft or other moving part of hard metal and the bearing face of soft metal. Steel on cast iron, steel on brass or bronze, and steel on various special soft bearing metals are examples of good wearing surfaces. The faces of bearings are frequently made of special bearing metals which are soft and which melt at a low temperature. Bearing facings made of such metals can be cast directly in place, and usually require no machining.

The original white-metal alloy for bearings was proposed by Isaac Babbitt in 1839 and was called babbitt metal. It was composed of 67 per cent tin, 22 per cent antimony, and 11 per cent copper. There have

been many variations from these proportions, some of them producing better metal for certain purposes.

HEAT-RESISTANT ALLOYS

Uses, Development, and Properties of Heat-resistant Alloys. Alloys that can carry stress under elevated temperatures are necessary in oil-refining plants, in high-pressure steam plants and lines, for steam-turbine blades, disks, and nozzles, and especially for blades, disks, and nozzles for gas turbines, superchargers for aircraft, and parts for jet-propelled aircraft. The stainless-steel alloy with 18 per cent chromium and 8 per cent nickel can be used up to about 1000°F. However, during the Second World War a demand arose for metals that could be used up to 1500°F. For gas turbines to compete with Diesel engines and steam turbines as a source of power, even higher temperatures are desirable. Metal under high-temperature service, say, in a gas turbine, must resist structural damage by distortion due to creep, fracture under long-continued steady load, fracture by "fatigue" under repeated stress, and damage by corrosion or erosion by hot gases.

During the Second World War a number of heat-resistant alloys were developed. Alloys with a cobalt base were developed and were strong and highly resistant to corrosion and to heat. However, they were expensive and very difficult to machine or to forge. They were usually precision-cast to shape. Another group of alloys were iron-base alloys with chromium and nickel as the important alloying elements. A chromium-nickel alloy similar to the stainless steel 18-8 alloy with about 2.5 per cent of molybdenum has also been used.

Under wartime conditions the cost of metal was usually a secondary matter, and for fighting airplanes long life was not expected. Under peacetime conditions the cost of metal and the available supply of some of the rarer ones, such as cobalt, may limit the use of many of the wartime alloys, and longer life will be expected for peacetime aircraft. In no field of metal production are the problems and the opportunities greater than in the field of heat- and corrosion-resisting metals. Some attempts have been made to use metals coated with refractory ceramic materials or to use ceramic materials for nozzles and blades, but it is not known just how far the development of ceramic materials for use in machine parts subjected to high temperature and high stress has been carried on (see Chap. XIII).

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Questions

1. What is the difference between a crystalline grain of metal and a piece of amorphous material?

2. What is the space-lattice of a solid? What is a face-centered cubic lattice, a body-centered cubic lattice? Name metals which have a body-centered lattice. A face-centered lattice.

3. What information as to crystal structure of a metal can be obtained by the use of X rays?

4. What are the slip planes in a crystalline grain of metal? How many slip planes in a face-centered cubic lattice, in a body-centered cubic lattice?

5. Which is the stronger, a metal made up of large crystalline grains or one made up of small crystalline grains, both metals having the same chemical content? Why?

6. Does the strength of a piece of metal depend wholly on the inherent strength of its crystalline grains? Explain your answer.

7. Do you agree with the statement that the ordinary formulas for stress and strain are not rigidly correct? If so, why do we continue to use them?

8. Why do sharp, narrow, long crystal grains (dendritic grains) weaken the crystalline grain?

9. Outline four processes which may be used during heat-treating a metal. What is the smallest number of processes which can be used in heat-treatment? Can you give an example?

10. Describe in detail a job of heat-treating which you have done, or one you saw done.

11. What is the difference between annealing and normalizing?

12. It is stated that annealing removes residual stresses from metal. Is this removal desired at all times? Describe conditions under which it is desirable and conditions (if any) under which it is not desirable.

13. What is "burned" steel? Why is it "unfit for use"?

14. Small rods of plain carbon steel can be quenched to as high a hardness as small rods of alloy steel, but this is not true of large rods of plain carbon steel and of alloy steel. Why?

15. Using Table XIV, pick out steel for the crank shaft of an automobile, for a structural shape to be used in the truss of a bridge, for a helical spring made up of 1-in. rod bent to shape hot, for the knife edge of a lever of a 20-ton platform weighing scale.

16. Give the reasons why sulfur, iron oxide, and phosphorus are regarded as injurious elements in steel. Are they always injurious?

17. Why is decarbonization injurious to steel? Name structural or machine members in which it is rather likely to happen. Why?

18. If you had to design a piece of machinery to resist a temperature of 1400°F., from which of the "three groups" of "stainless" steel would you choose the metal for that piece of machinery?

19. Looking at Fig. 59, why is an alloy with more than 40 per cent of copper undesirable?

20. What is the nominal difference between a brass and a bronze?

21. Sheet metal made of an aluminum-clad alloy is somewhat weaker than a sheet of the same thickness made of aluminum. Under what conditions would the aluminum-clad sheet be better than the aluminum sheet?

22. Why is babbitt metal a good metal for bearings? Would it be a good bearing metal for a large shaft which revolved very slowly? If not, what metal would you choose for such a bearing? Why?

23. It has been suggested that a ceramic material would withstand higher temperatures than any metal yet known; can you see any reason why it might not be a good material for gas-turbine blades?

24. Why is heat-treating of nonferrous metals less frequent than heat-treating of iron and steel?

25. What special heat-treatments are used for nonferrous metals? Name some nonferrous metal which can be strengthened by heat-treatment.

26. Define precipitation hardening and name a metal which is strengthened by that process. What other name is sometimes given to that process? Why?

CHAPTER XI

STRENGTHENING METAL PARTS BY SURFACE TREATMENT, WELDING, POWDERED METALS

Importance of Surface Condition in Metals. Structural damage, whether by failure of elastic strength, by creep, by fracture, by wear, or by corrosion, if and when it occurs, usually starts at or very close to the surface of a structural or machine part. Exceptions occur in the failure of parts under direct tension or compression and parts with internal defects such as flakes or shatter cracks or other "metallurgical notches." Under bending or torsion the maximum stress is usually at the surface, and a defect at or immediately below the surface may greatly weaken the part, especially under repeated stress. A crack may be started if the stress at the surface equals the endurance limit of the weakened metal and, once started, the stress concentration caused by the crack often causes it to spread through the stronger metal below the cracked surface metal.

Surface treatments that increase the strength of a zone of metal at the surface increase the strength of the part, especially against bending, torsion, and wear, and a corrosion-resisting surface treatment, of course, increases the resistance to corrosion, which can get at the metal only through the surface. Surface treatments are especially effective in increasing resistance to fracture under repeated stresses.

Figure 61(a) is a diagram of a metal bar under bending or torsion. It is stressed so that in the outer fiber OA the stress AB is equal to the stress at failure of the metal in the bar, failure of elastic strength, fatigue strength, strength in tension (bending), or strength in shear (torsion), as the case may be. Then suppose another piece of the same bar is given a surface treatment which increases the strength of the metal to AC in Fig. 61(b) and suppose the effect of this surface treatment extends to the depth t. Then to cause failure in the base metal of the bar, the stress at A' in Fig. 61(b) must be $A'B'$ which is equal to AB in Fig. 61(a). Then the stress at the extreme fiber of the surface-strengthened bar is AB'' and the strength of the bar to resist bending or torsion is increased in the ratio $AB''/A'B'$ which equals AB''/AB.

Figure 61(c) shows a piece of the same bar surface strengthened and under direct axial tension with uniform distribution of stress over the cross section. Then the stress that will cause failure in the base metal

is still AB, assuming that the modulus of elasticity of the strengthened surface zone is not appreciably different from that of the base metal in the bar. Hence the strength of the bar under torsion is still AB, and the strengthened surface zone has not added much to the strength of the bar to resist direct tension. The foregoing outline is a rather crude general picture of the effect of surface strengthening.

Unless the surface zone is rather deep, under bending or torsion a fracture may start in the weaker base metal at or near the junction

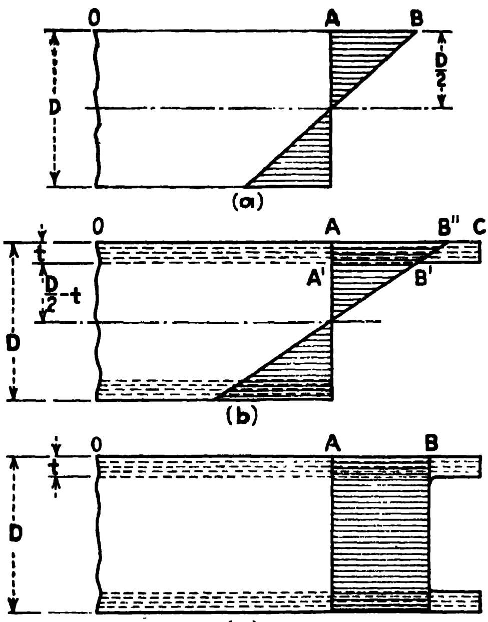


FIG. 61. Strengthening effect of a hardened surface zone on a metal part.

of base metal with strengthened surface zone. Figure 62 shows the fatigue fracture of a case-carburized specimen. The fracture started at a nucleus N near the inner border line of the "case" and spread inward and outward till complete fracture of the specimen occurred.

Types of Surface Treatment and Residual Stresses Set Up. Surface treatments in common use may be divided into four types:

1. Surface alloying treatments, including carburizing and nitriding of iron and steel parts.

2. Surface heat-treatments, including flame hardening and electric induction hardening.

3. Surface coatings, including electroplating, galvanizing (zinc coating), tin plating, and "cladding" of metals with rolled-on thin sheet metal.

4. Cold-working, including cold-stretching, cold-rolling, cold-drawing, polishing, machining, shot peening, and repeated stress.

Surface alloying treatment changes the chemical composition of the surface zone of the metal treated and adds strengthening alloying elements. In some cases heat-treating is applied to the part after the alloying treatment has been applied. Surface heat treatments can be used to strengthen a surface zone of the metal. Electroplating is used chiefly for protection against corrosion.

Cold-working of metals strengthens and embrittles them by the mechanical distortion of the crystalline structure, with consequent distortion of space-lattice cells and distortion and misalignment of slip planes within crystalline grains, thus increasing resistance to slip.

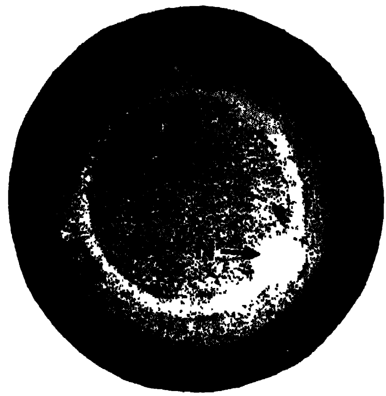


FIG. 62. Fracture section of a carburized steel fatigue specimen. The fracture started not at the surface, but at the nucleus N at the junction of the carburized case and the base metal core.

Each of these types of surface treatment sets up stresses in the metal so treated. These stresses are called residual stresses and may be either beneficial or injurious to the strength of a machine part, depending on whether they oppose the dominant applied stresses that the part must withstand in service or add to those applied stresses.

Residual stresses may be divided into two classes: stresses affecting an appreciable volume of the metal and stresses determinable by measuring the minute changes in a sample part when metal is removed from it. For example, the longitudinal residual tensile or compressive stress in a round shaft can be determined approximately by measuring the change of length along longitudinal gage lines on the surface, the change of length which occurs as successively larger axial holes are bored through the shaft. (References 1 to 3 at the end of this chapter describe methods of determining the magnitude of residual stresses.)

It is sometimes stated that fracture failure, either under a single load or under repeated load, is always caused by a tensile stress. A fracture involves the separation of atoms or space-lattice units, or of small particles of metal. The experimental evidence today indicates that fracture starts on a plane along which slip is occurring under a shearing stress. On such a plane, especially as slip occurs, the atomic structure must be very badly distorted, and it is easy to picture tensile stresses

acting on microscopic areas at right angles to that plane of slip. Once a crack gets started, there occurs high stress concentration at its ends, and the crack becomes self-extending and frequently seeks a path at right angles to the principal tensile stress in its vicinity.

SURFACE ALLOYING TREATMENTS

Carburizing. The *case-carburizing* or *case-hardening* process sets up in iron and steel a hard surface layer of high-carbon steel. In this process small particles of iron or steel are packed in some carbonizing agent, such as charcoal, leather scraps, bone dust, or potassium cyanide, or are

TABLE XV. INCREASE OF FATIGUE STRENGTH OF STEEL BY CARBURIZING
Data from tests made in the Talbot Laboratory, University of Illinois

Item	Steel	Treatment	Depth of case, in.	Endurance limit under reversed bending, lb. per sq. in. — Millions of cycles of stress to fracture: 0.01	0.10	1.0	10	Indef. large
(1)	0.20 per cent carbon structural steel	As rolled, not carburized	0	51,000	39,000	31,000	28,000	28,000
(2)	0.20 per cent carbon structural steel	Carburized, then slow cooled	0.078	55,000	46,000	40,000	40,000	40,000
	Ratio (2)/(1)	...	....	1.07	1.18	1.29	1.43	1.43
(3)	0.20 per cent carbon structural steel	Carburized, then oil-quenched	0.078	130,000	95,000	80,000	80,000	80,000
	Ratio (3)/(1)......	....	.....	2.54	2.45	2.58	2.84	2.84
(4)	Chrome-nickel steel: carbon, 0.20%; nickel, 1.25%; chromium, 0.6%	As rolled, not carburized	0	61,000	54,000	46,000	39,000	38,000
(5)	Chrome-nickel steel: carbon, 0.20%; nickel, 1.25%; chromium, 0.6%	Carburized, then oil-quenched	0.032	154,000	122,000	100,000	90,000	90,000
	Ratio (5)/(4)........	....	....	2.52	2.26	2.17	2.30	2.37

NOTE: The fatigue specimens were round, 0.3 in. in minimum diameter.

exposed to a hydrocarbon gas and heated for a period of time. The depth of the hardened surface zone or "case" depends on the temperature and the length of time of the carburizing process. The strength and the hardness of the particle may be increased by a quench, or quench and draw, following the carburizing.

Carburizing improves surface hardness and therefore wear. It also increases the elastic strength of steel pieces to be subjected to bending or to torsion. The resistance to repeated stress (fatigue strength) may be

very markedly increased by carburizing followed by heat-treating. Table XV gives typical results of fatigue tests of carburized steel and steel not carburized. It will be noted how much the heat-treatment of the structural steel after carburizing increased the fatigue strength above that of the same steel carburized and then slowly cooled. It will also be noted that the proportional increase in fatigue strength by carburizing and heat-treatment was fully as great for the alloy steel tested as for the low-carbon structural steel.

Nitriding. Nitrogen in steel embrittles it but makes it hard and strong. A process is in common use in which steel is exposed to ammonia gas, NH_3, at an elevated temperature. This gives the steel a hard surface zone or "case" somewhat similar to the case given by carburizing. Not all steels nitride well, and steel with a decarburized surface does not seem to be suited for nitriding. Mildly tempered steel (see page 77) takes a nitrided case better than softer steel. Nitriding is especially useful for increasing wear resistance. It can also be used to increase elastic strength in bending and flexure and to increase fatigue strength. Table XVI gives results of fatigue tests of alloy specially designed for nitriding and gives some idea of the proportional increase in fatigue strength to be obtained by the nitriding process.

SURFACE HEAT-TREATING

Flame Hardening. Steel parts may have a surface zone hardened and strengthened by slowly moving the flame of an oxyacetylene torch over the area to be treated, following the flame with a stream or spray of water or by an air blast as a quench. This process is called "flame hardening." This process is especially applicable to pieces that are too large for effective heat-treatment in a furnace, or in which furnace heat-treating sets up dangerous residual stresses. It is also useful in pieces in which hardening is desirable over only limited areas. For example, it is desirable that gears have hard surfaces along the faces of the teeth and, sometimes, along the fillets at the roots of the teeth, but not over hubs and plates or spokes. The end hardening of the ends of railroad rails is desirable to reduce the "batter" produced at the rail joints where the wheel load causes excessive distortion. The rails, if heated in a furnace and hardened throughout after rolling, would be badly distorted, require expensive straightening, and increase the work of drilling and cutting rails as is frequently necessary in service. Localized hardening seems to be the best process for rail end hardening, and flame hardening is one of the processes quite widely employed.

Although flame hardening produces much less distortion than furnace hardening, the distortion is troublesome in some cases. Distortion may

be minimized by symmetrical flame hardening on both sides of the piece, especially if it is a thin plate.

The steels that respond to flame hardening include the plain carbon steels with carbon content 0.35 per cent and higher, and some of the alloy steels. The alloy steels usually are more difficult to flame-harden satisfactorily than the plain carbon steels, and each alloy steel requires experimentation to develop satisfactory methods. Pearlitic cast iron and malleable cast iron may be successfully flame-hardened. Flame hardening has very little beneficial effect on decarburized steel.

TABLE XVI. INCREASE IN FATIGUE STRENGTH OF STEEL BY NITRIDING
Data from tests made in the Talbot Laboratory, University of Illinois

Item	Steel	Treatment	Depth of case, in.	Endurance limit under reversed bending, lb. per sq. in. — Millions of cycles of stress to fracture: 0.01	0.10	1.0	10	Indef. large
(1)	Special nitriding alloy, carbon, 0.32 per cent	As rolled, not nitrided	0	70,000	61,000	53,500	49,000	49,000
(2)	Special nitriding alloy, carbon, 0.32 per cent	Nitrided	0.03	125,000	95,000	81,000	69,000	68,500
	Ratio (2)/(1)........	....	. .	1.78	1.56	1.52	1.41	1.40

NOTE: The fatigue specimens were round, 0.3 in. in minimum diameter.

The flame-hardening process produces a hard surface zone with an unhardened "core." In steels the surface may be hardened up to Brinell 600, but this gives too brittle a surface metal. The surface hardness depends on the quench used. The mildest is cooling of the heated steel by conduction to the unheated mass of metal. Cooling by an air blast produces harder surface metal than this mass cooling, and quenching by a stream or spray of water produces still harder surface metal. The depth of the hardened surface zone varies from a very thin skin to ¼ in., depending on the rate of travel of the flame over the surface. The relative motion of torch and plate may be hand-controlled or, in most cases, may be machined-controlled to produce greater uniformity of surface hardness.

The flame-hardening process usually sets up residual stresses in the hardened surface zone. Since some of the residual stresses may be tensile, it is desirable, if feasible, to follow the quench by a stress-relieving treatment at 350 to 400°F. This treatment is best made in a furnace, in air, or in an oil bath heated within that temperature range.

It has been pointed out that distortion due to flame hardening may be minimized by symmetrical flame hardening on both sides of a machine part. However, this minimizing of distortion does not imply minimizing of residual stress. For example, consider the case of a flat plate flame-hardened on one side. It is distorted and residual stresses are set up. Now, if the other side is similarly flame-hardened, residual stresses are set up which tend to straighten the plate. The latter is then less distorted, but it has residual stresses both in the hardened zone on the upper side and in the hardened zone on the lower side, and a stress-relieving treatment is, in general, desirable.

The flame-hardening process may be used to strengthen the metal at regions of localized stress concentration. However, residual stresses may be set up which may partly or wholly neutralize the benefits of the flame-hardening process.

The increase of strength of a machine part due to flame hardening may be roughly estimated by considering that the strength of the surface zone over about 80 per cent of its depth is proportional to its Brinell

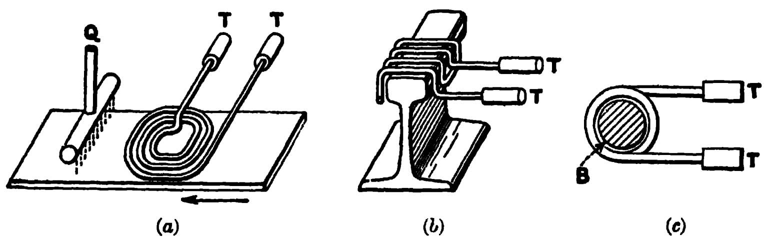


FIG. 63. Diagram sketches of induction-heating devices. *TT'*, terminals of high-frequency electric circuit. *Q*, distributor for air or water for quenching. *B*, cross section of bar to be hardened.

hardness. With the strength and the Brinell hardness of the base metal known, strength of the metal in the hardened zone can be estimated and the strength of the part estimated by the method suggested by Fig. 61(*b*) and the accompanying text.

Induction Hardening. This is a form of surface heat-treatment in which the necessary heat is supplied by the electric hysteresis losses when a piece of metal carries very high-frequency electric current. The high-frequency current is supplied by induction from a coil that carries high-frequency current from a multipole high-speed generator (9,000 to 12,000 cycles per second), from a spark-gap apparatus, or from vacuum tubes (100,000 cycles per second and over). Figure 63 shows several forms of induction-heating apparatus in diagram. In Fig. 63(*a*) is shown a "pancake" coil of wire carrying high-frequency current and fixed close

above a plate of steel, which can be moved under it as shown by the arrow. A short distance beyond the coil is a tube with multiple discharge holes from which a blast of air or streams of water can be discharged against the plate to cool it rapidly. Figures 63(*b*) and 63(*c*), respectively, show an induction-hardening coil for a railroad rail head and for a round rod. In production the control of current, of motion of the article to be induction-hardened, and the timing and amount of cooling medium can be automatically controlled.

The induction-heating process acts very quickly and requires very careful control. Rods, plates, and rails can be heated above red heat in seconds rather than in minutes, and the critical temperature for the steel is indicated by a falling off of the current in the coil. The proper temperature for any particular job and the choice and proper rate of flow of cooling medium are matters of experiment. The induction-heating process is especially adapted to mass production of surface-heat-treated articles. It has been used in end-hardening rails, in heat-treating agricultural-machinery parts, in heat-treating shafts at critical points, and for many other structural and machine parts.

Its limitations are much the same as those of flame hardening. It has little effect on low-carbon steel and would not be of much value in raising the strength of decarbonized steel, such as that shown in Fig. 58.

Surface Heat-treating of Ends of Railroad Rails. A striking illustration of the uses and limitations of surface heat-treating is found in the report of field tests on a test length of track in service. The track contained 900 test rails. One hundred rails were unhardened, and eight end-hardening processes were used, each on 100 rails. The test track has been in service since June, 1939, and in May, 1945, slightly more than 267,000,000 tons of traffic had passed over it. The end-hardening processes included flame hardening with a hand-held oxyacetylene torch, with mechanically propelled oxyacetylene burners, with gas heat at the rail mill, by electric induction hardening at the rail mill, by quenching direct from the rolling heat, and by quenching a rail which after rolling had been normalized in a separate furnace. The results did not serve to show any marked distinction between the heating processes but did show a marked distinction between the quenching processes.

Table XVII shows a summarized result of these tests. It is seen that all the end-hardening processes reduced the batter of rail. However, the processes using the relatively mild air quench and the process using quench by conduction from cold metal showed fully as great a reduction of batter from the batter of the unhardened rail as did the water-quenched rails. The air-quenched rails and the rails quenched from the cold metal showed a much smaller number of cracked rails. For this par-

ticular service, surface heat-treatment to a Brinell hardness of 360 to 369 would seem to be desirable.

TABLE XVII. END-BATTER TESTS OF RAILROAD RAILS

The test rails had been in service nearly six years and had carried 267,372,180 tons of traffic when they were removed from the track and tests were made in the Talbot Laboratory, University of Illinois. There were 900 test rails in all, 100 rails of each of 8 treatments and 100 unhardened rails.

Type of quench	Number of types of treatment	Brinell hardness no.			End batter[1] of rail, in.			Rail ends cracked, per cent
		Minimum	Maximum	Average	Minimum	Maximum	Average	
Unhardened........	1	...	...	287	.....	....	0.022	1.50
By conduction from unheated part of rail..............	1	. .	. .	369	. . .	.....	0.012	1.50
Blast of air.........	2	361	374	368	0.012	0.012	0.012	1.75
Water quench.......	5	364	426	390	0 013	0.179	0 015	9.00

[1] Batter is the permanent depression of the tread of the rail at the rail joint.

ELECTROPLATING AND MECHANICALLY APPLIED COATINGS

Purposes of Applied Coatings on Metal Parts. The commonest use of a metal coating is to protect the base metal from corrosion. Two types of such coatings are in use. In one the protective coating is less resistant to corrosion than the base metal and protects small exposed areas of the base metal by the electrolysis of the coating metal rather than the base metal. Obviously this protection lasts only until the protective coating is destroyed. The coating is anodic and the base metal cathodic. Zinc and cadmium are anodic coating metals.

In the other type of protective coating, the coating is more resistant to attack than is the base metal. This is true of nearly all the electrodeposited metals except zinc and cadmium. The common coatings of this type are nickel, tin, lead, and chromium. Such coatings afford complete protection against corrosion of the base metal only if they are free from pores and cracks. This is illustrated by the corrosion of tin plate at scratches that penetrate the thin coating of tin. The most practical method of decreasing the porosity of the coating is to increase its thickness. This sometimes raises the problem of residual tensile stresses, which are sometimes set up between the plating and the base metal.

From the strength viewpoint the great value of chromium plating is increased resistance to wear due to the great hardness of the chromium.

Reference 4 at the end of this chapter gives several instances in which chromium plating has actually reduced the fatigue strength of a metal part.

Today, in the best practice, coatings are usually electroplated. An exception is the coating of pure aluminum applied to aluminum-alloy plates and sheets to protect the alloy from corrosion. The aluminum alloy is run hot through rolls, "sandwiched" between the sheets of pure aluminum. This process is called "cladding" and the "sandwich" is called "clad" metal, Alclad in the case of aluminum. Recently "cladding" with some other metals has been successfully used.

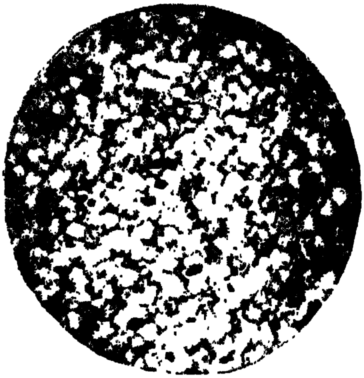
COLD-WORKING

Cold-working and Hot-working Compared. Cold-working is done when metal is permanently deformed by rolling, drawing, peening, twisting, stretching, or compressing at a temperature below the range of temperature within which recrystallization takes place. Hot-working is done when such distortion is done above that critical temperature range. Hot-rolling nearly always produces stronger metal than cast metal. Hot-working causes the grain growth to start from many nuclei in a piece of metal, and the grain size is smaller than in cast metal. Such weakening crystalline structures as dendrites (see Fig. 56(*c*), page 134) rarely occur in hot-rolled metal. However, the crystalline grains are regular in shape, and their space-lattice cells are but little distorted or misaligned, unless by alloying elements.

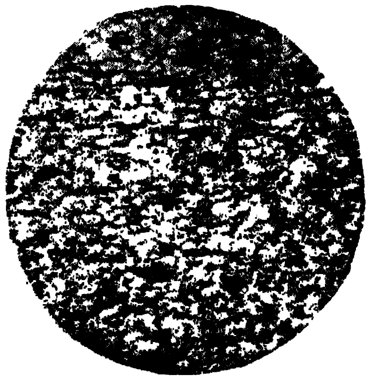
In cold-worked metal the grain structure is distorted (see Fig. 64, page 163) and the space-lattice cells are presumably much distorted and misaligned. This distortion increases the strength of the metal if not carried to the point of starting a crack. Too heavy cold-working exhausts the ductility of the metal. Cold-working, then, accomplishes somewhat the same kind of results as alloying or heat-treating, by direct mechanical distortion.

Uses and Limitations of Cold-working. Cold-working is frequently used when localized hardening or strengthening of a machine part is desired. Illustrations of this use may be found in the cold-rolling or shot peening of shafts at fillets or of the root of screw threads. Cold-working can nearly always be made to set up residual stresses which resist the working stresses applied to the part and, applied to a localized area, causes little general deformation of the piece. In many cases cold-working by rolling or by shot peening is less expensive than polishing the surface of a machine part, and it gives greater strength than polishing, especially under repeated stress. Cold-working by hammer peening can be carried out without any expensive equipment and is useful for small

special jobs. Cold-working can be used to offset partially decarburization of steel (see Fig. 58). Cold-working can be used to strengthen the nonferrous structural metals, most of which do not respond to heat-treating as do the ferrous metals. Cold-working is especially effective in strengthening sheet metal.

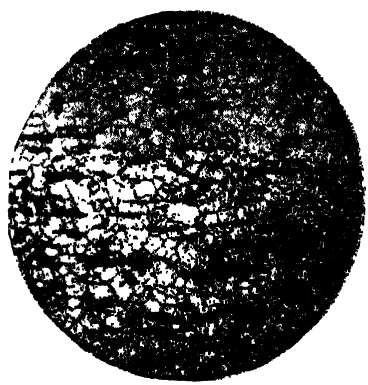


(*a*) Annealed.



(*b*) Fifteen per cent reduction from original cross section.

(*c*) Sixty per cent reduction from original cross section.



(*d*) Annealed after cold-drawing.

FIG. 64. Effect of cold-drawing and annealing on steel wire with 0.08 per cent carbon. Magnification 80 times. (*Micrographs by John F. Tinsley. Courtesy of Iron Age.*)

Cold-working, except on relatively thin plates and shapes, affects the metal to only a relatively shallow depth and may therefore be expected to be less effective on large, thick pieces than on small, thin ones. However, cold-work can be used to offset the effect of "stress raisers" even on large pieces. The peak stress of a stress raiser extends only a short distance into the metal below the surface, and the effect of cold-work usually reaches deeper than the peak stress at a hole, notch, or fillet.

Much study and experimentation are needed to devise an effective technique of cold-working for any particular machine or structural member. This is true of all forms of surface treatment.

Cold-work and Surface Shape and Smoothness. The ideal surface of a metal part is an absolutely smooth one. Needless to say, such a surface is never obtained, and tests by various laboratories indicate that a finer finish than that obtained with No. 00 emery cloth with the scratches in the direction of the principal tensile stress, or nearly so, gives but little higher results. Such a finish is a quite satisfactory "standard" finish, especially in view of the difficulty of *preserving* a high finish on most machine parts in service.

Surface smoothness has decidedly more effect on resistance to repeated stress (fatigue strength) than on elastic strength or on tensile strength. The matter of effect of surface smoothness on fatigue strength is further discussed in connection with surface treatment by shot peening.

Several types of surface treatment by cold-working may now be considered, together with typical results as shown by tests.

Cold-drawing. Metal rods and wire are usually drawn through dies made of very hard steel, rather than being rolled longitudinally. The stress over the cross section of the rod is fairly evenly distributed and there are only small residual stresses. The rod comes out nearly straight. Cold-drawing increases the yield strength of the metal considerably and increases to a somewhat lesser degree the tensile strength and usually the fatigue strength (see Table XVIII).

Cold-rolled Machined Shafts. Machined shafts may be cold-rolled by the rolling rig shown in Fig. 65. The shaft is mounted in a lathe and the rolling rig fed along the shaft by the lathe feed. The face of the rollers is rounded to fit fillets or grooves in the shaft. A rig of this kind is especially adapted to strengthen the shaft at press fits, fillets, grooves, or threads, and to offset, partly at least, the stress concentrations. Table XVIII, items 6 to 11, gives results of tests by Horger at the Timken Laboratories on two shafts, one of chrome-nickel steel and the other of 0.36 carbon steel, both shafts normalized and tempered. The long-time fatigue strengths of the rolled filleted shafts were about 1.60 times the strengths of the filleted shafts not rolled, and were about 90 per cent of the long-time fatigue strengths of small polished specimens without fillets.

This rolling method of surface strengthening is very useful in strengthening decarburized areas on a steel surface and in offsetting much of the stress concentration found in shafts and axles. Figure 66 shows typical stress concentrations whose damaging effects may be largely overcome by cold-rolling or by shot peening. In the case of oil holes, which are very troublesome stress raisers, the rolling process cannot be used. However,

TABLE XVIII. EFFECT OF COLD-DRAWING AND OF COLD-ROLLING ON STEEL RODS AND SHAFTS
Tests at Timken Laboratories, Canton, Ohio, and at the University of Illinois

Item	Metal	Treatment	Yield strength, lb. per sq. in.	Tensile strength, lb. per sq. in.	Elongation in 2 in., per cent	Endurance limit under reversed bending, lb. per sq. in. Millions of cycles of stress to fracture: 0.01	0.10	1.0	10	Indef. large
(1)	½-in. rod, 0.18% carbon steel	As rolled	40,300	61,500	41	50,000	41,000	32,000	28,000	28,000
(2)	½-in. rod, 0.18% carbon steel	Stretched till diam. was reduced to 0.48 in.	63,300	67,600	22	55,000	45,000	38,000	35,000	35,000
	Ratio (2)/(1)	...	1.61	1.10	0.54	1.10	1.10	1.18	1.25	1.25
(3)	½-in. rod, 0.18% carbon steel	Stretched till diam. was reduced to 0.44 in.	71,500	73,400	14	60,000	53,000	46,000	41,000	41,000
	Ratio (3)/(1)	...	1.78	1.19	0.34	1.20	1.29	1.43	1.47	1.47
(4)	½-in. rod, 0.18% carbon steel	Bent cold through 45°, then straightened	...	...	...	...	46,000	35,000	30,000	30,000
	Ratio (4)/(1)	...	...	...	...	...	1.12	1.09	1.07	1.07
(5)	½-in. rod 0.20% carbon steel	As received, cold-rolled	71,000	86,800	14	73,000	59,000	45,000	41,000	41,000
	Ratio (5)/(1)	...	1.76	1.41	0.34	1.46	1.44	1.40	1.47	1.47
(6)	Chrome-nickel steel shaft, filleted	Normalized and tempered, not rolled	...	131,600	15	...	...	...	...	30,000
(7)	Chrome-nickel steel shaft, filleted	Cold-rolled	...	...	...	...	...	...	...	50,100
	Ratio (7)/(6)	...	...	...	...	...	...	...	...	1.67
(8)	Chrome-nickel steel shaft, no fillet	Polished spec. not rolled	...	...	...	...	...	...	...	56,900
	Ratio (8)/(6)	...	...	...	...	...	...	...	...	1.13
(9)	0.36% carbon steel shaft, filleted	Normalized and tempered, not rolled	...	...	...	...	...	...	...	23,300
(10)	0.36% carbon steel shaft, filleted	Normalized and tempered, cold-rolled	...	...	...	...	...	...	...	36,400
	Ratio (10)/(9)	...	...	...	...	...	...	...	...	1.56
(11)	0.36% carbon steel shaft, no fillet	Normalized and tempered, not rolled	...	...	...	...	...	...	...	39,100
	Ratio (11)/(10)	...	...	...	...	...	...	...	...	1.07

the surface of the oil hole can be cold-worked by driving or pressing into it a slightly tapered lubricated pin and then pulling it out. Screw threads may be strengthened by this rolling process by the use of rollers formed to fit the radius at the root of the thread.

This rolling process of surface strengthening sets up severe residual stresses in the shaft. There are heavy longitudinal compressive stresses

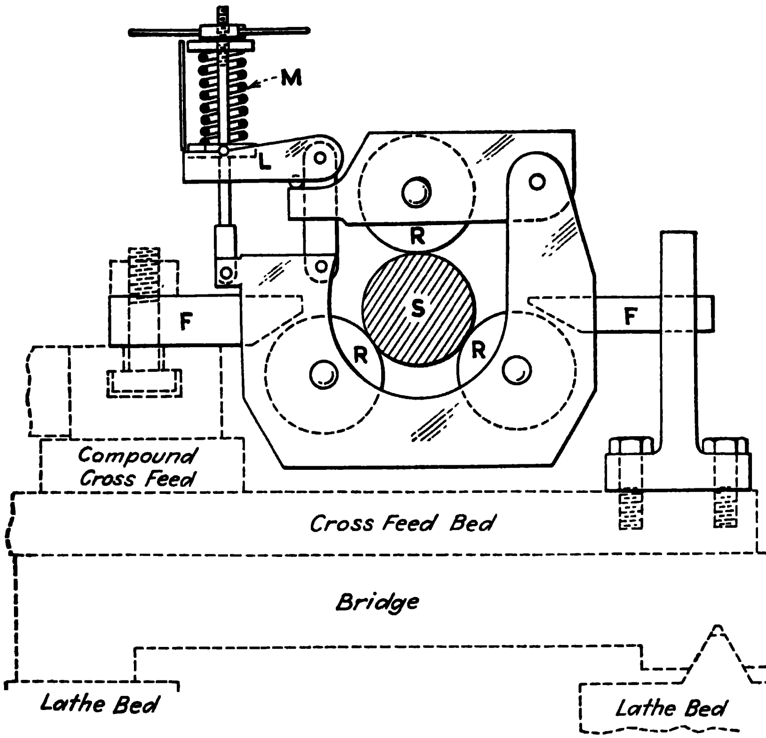


FIG. 65. Attachment to a lathe for cold-rolling the surface of a shaft or an axle. *M*, calibrated spring for measuring radial load applied to rolls. *L*, load-multiplying lever. *R*, three rolls with hardened convex faces. They are moved along the shaft or axle to be surfaced by cold-rolling as the bridge of the lathe is fed along the lathe bed. *S*, cross section of shaft or axle to be surface-hardened by cold-rolling. *F*, floating arms to transfer the motion of the bridge along the lathe bed to the rolling attachment. (*Courtesy of Dr. O. J. Horger, Timken Roller Bearing Co. Laboratories.*)

in the surface zone. There are radial stresses which are zero at the surface. In the *core* of the shaft there are light longitudinal and circumferential tensile stresses and radial stresses. The longitudinal compressive stresses in the surface zone tend to offset any applied longitudinal tensile stresses. The relative amount of strengthening that can be assigned to the residual compressive stresses and to the improvement

of strength of material by the distortion of the atomic structure of the metal has not been determined. The net result of possible strengthening of metals by cold-working has, however, been well demonstrated by many laboratories.

Permanence of Residual Stress. Experiments have shown that the residual stresses due to cold-work may be removed by a very few cycles of stress as great as the yield strength of the metal. A considerable part of

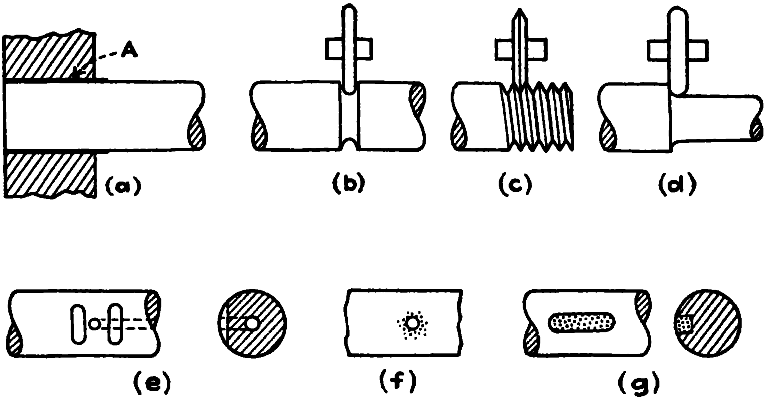


FIG. 66. Typical examples of the use of cold-rolling or of shot peening to lessen the effects of stress concentration in structural and machine parts. (*a*) Cold-rolling or shot peening of the surface indicated by heavy lines will increase the fatigue strength of the steel and set up compressive residual stresses in the surface of the shaft at *A*, thus lessening the weakening effect of the stress concentration at *A*. (*b*) Shot peening or cold-rolling by a formed roller will lessen the effects of stress concentration at the bottom of a groove. (*c*) Cold-rolling with a formed roller will lessen the effects of stress concentration at the root of a screw thread. Shot peening can be used only if the radius of the shot is less than the radius at the root of the screw thread. (*d*) Cold-rolling or shot peening will lessen the effect of stress concentration at fillets. (*e*) Transverse grooves near an oil hole on either side will lessen the effects of stress concentration at the oil hole. Cold-rolling or shot peening the grooves would help still further. (*f*) Stress concentration at an oil hole may also be relieved by shot peening the surface around the hole or by driving a tapered pin into the oil hole and then removing it. (*g*) Shot peening may be used to relieve stress concentration at the corners of a keyway.

the residual stresses can be removed by 1,000,000 cycles of stress two-thirds of the yield strength. It seems as if these residual stresses were not entirely stable, but were removed rapidly by yield-strength stresses and much more slowly by cycles of lower stress.

Shot Peening. Shot peening is a process of cold-working the surface zone of a structural or machine part by driving a rain of metallic shot against the surface. The shot are usually chilled cast-iron shot or hardened malleable cast-iron shot, and the driving force is furnished by an air blast or by the centrifugal force of shot released from the rotating

blades of a wheel. Its effect in cold-working the metal is qualitatively like that of the rolling process just discussed, but the depth of penetration of the hardening effect is less with shot peening. The technique of shot peening involves determining the optimum size of shot, velocity of shot, and time of exposure to the rain of shot. To obtain good results it is essential that, so far as possible, broken shot be removed from the blast and not returned to the container and used over again.

Shot peening, like other cold-work surface treatments, adds to the yield strength of parts in bending and in flexure but does not add greatly to the strength of parts in direct tension or compression. Figure 67 shows the effect of shot peening on the fatigue strength of two steels, one a low-carbon steel and the other a heat-treated chrome-molybdenum steel with its surface hardened by carburizing before being shot peened. It may be seen that shot peening increased the fatigue strength even of the already hardened alloy steel. Data are not available to make a precise comparison between the effectiveness of shot peening and of the cold-rolling process described in preceding paragraphs, but in a general way the two seem to produce about the same improvement when a proper technique has been developed. Figure 67 shows the marked improvement in fatigue strength of specimens due to polishing as well as the even more marked effect of shot peening. It is of interest to note that a honing process used after shot peening gave the greatest improvement in fatigue strength observed in the series of tests whose results are shown in Fig. 67.

Shot peening produces residual stresses much as does the cold-rolling process, and these stresses in the surface zone are two compressive stresses at right angles. This is made evident by the double buckling of a square steel plate shot-peened on one side.

In most cases shot peening can be used to offset, at least partly, the effect of stress concentrations in a machine part, as is noted in Fig. 66. It cannot be used to strengthen very fine-pitch screw threads, because the smallest shot used will not penetrate to the rounded root of the thread. It is, however, effective for strengthening large- and medium-sized screw threads.

Some of the important advantages of shot peening may be summarized as follows:

It can be applied to irregular shapes, with which heat-treating might cause excessive distortion, and to pieces to which drawing and rolling processes are not applicable.

It can be applied to finished parts such as springs, and to specific areas on finished parts. It can be applied to fillets on a shaft to mitigate the bad effects of stress concentration, or to the body of the shaft to resist pitting corrosion.

It can be applied to gear teeth to lengthen fatigue life, without causing appreciable distortion, by producing a surface with greater resistance to wear and to pitting under heavy localized stress.

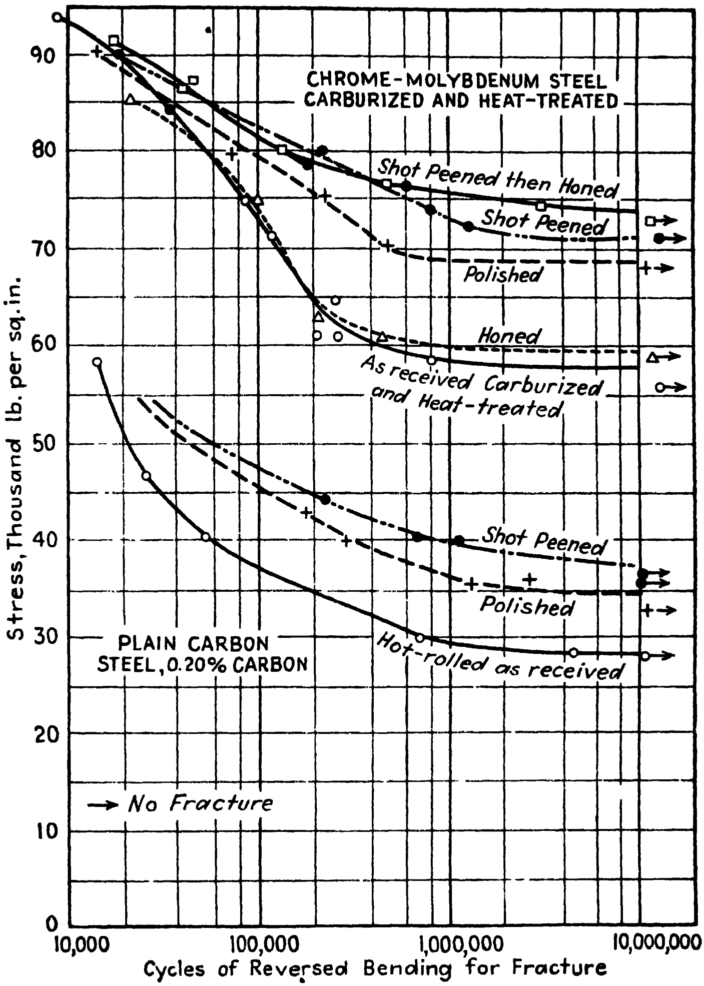


FIG. 67. *S-N* diagrams showing effects of different surface treatments on the fatigue strength of two steels.

In some cases its use does away with the necessity of polishing a part for surface finish, with an improvement in strength and a reduced production cost.

Polishing and Repeated Stress. Polishing metal surfaces sets up a very thin surface zone in which residual stresses are set up and cold-work distorts the space-lattice cells and strengthens the material. Comparing

the fatigue strengths developed in the tests whose results are shown in Fig. 67, it will be seen that polished specimens both of low-carbon steel and of very hard carburized alloy steel develop endurance limits not much below those developed by shot peening, and well above the endurance limits of the metal in the "as-received" state.

Cycles of stress above the yield strength of a metal cold-work the metal, and it has been shown in several laboratories that cycles of stress below the yield strength can increase the endurance limit of metal if repeated hundreds of thousands of times. This seems like cumulative cold-work, perhaps due to microstresses in the crystalline grains of the metal—stresses which, when repeated thousands of times, cold-work the metal slightly.

Cold-work during Machining of Metals. Under the action of a cutting tool, metal is sheared off in a thin chip and, at the same time, there is heavy localized pressure of the tool against the metal. This pressure seems to cause cold working in the surface. Whether the net result of machining is an increase or a decrease of strength is probably determined by the net result of the cold-working, strengthening effect of the pressure of the cutting tool, and the smoothness or roughness of the surface left as the chip is cut off from the metal by the cutting tool. It is quite possible, too, that after a heavy cut there may be left residual tensile stresses in the metal.

WELDING[1]

Types of Welds. Welds in steel and other metals may be divided into two classes: (1) welds made at a plastic heat and (2) welds made by complete fusion of the adjacent metal in the parts joined. Plastic welding is accomplished by bringing the edges to be joined up to a temperature a little below fusion and then pressing or hammering them together. Wrought iron can be readily welded by plastic welding, soft steel can be welded without much difficulty, but high-carbon steel can be thus welded only by a skilled workman. Cast iron cannot be welded by plastic welding.

Plastic welding is sometimes done in a forge fire, as is the usual case for welding rods or chain links, and sometimes by the use of electric current passing through the parts to be welded and supplying the necessary heat. Figure 68 shows in diagram rolls for welding pipe. Special welding

[1] It is doubtful whether welding should be thought of as the "processing" of a metal, except possibly when it is used to build up worn metal or places where small pieces have "shelled out" of a metal surface. However, a very brief discussion of several types of welding seems in place in a textbook on materials, and it is placed in this chapter.

machines using electric current are used for welding rods, chain links, and other machine parts; these are to be distinguished from the machines, noted a little later, which are for making electric welds by fusion of the metal. Spot welding is a special method of welding by the use of electric current or of the oxyacetylene torch, and its operation is shown in

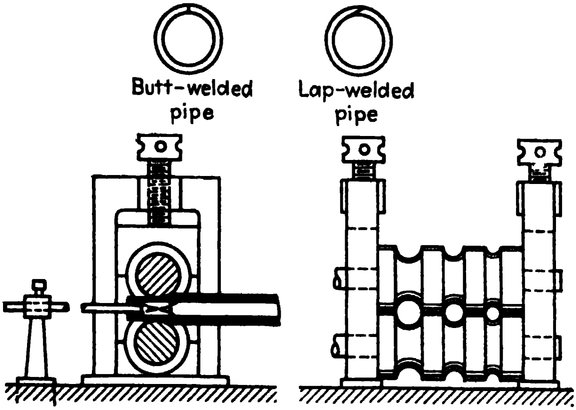


FIG. 68. Diagram of pipe-welding rolls.

principle in Fig. 69. Alternating current is supplied at low voltage by a transformer T and passes through electrodes CD and the pieces EF to be joined, or the flames of oxyacetylene torches are applied at C and D. Pressure is applied to the electrodes, and sufficient heat is generated in the metal to bring a small spot to a plastic welding heat, and thus to "tack" the pieces together. Spot welding is used for fastening together pieces which do not have to transmit heavy stress, or for tacking together pieces which are to be more thoroughly welded by a fusion process of welding, as described in the next paragraph.

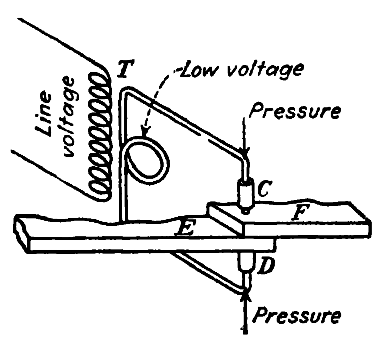


FIG. 69. Diagram of spot-welding apparatus.

Fusion Welding. If the edges of two adjacent pieces of metal are heated to a temperature of fusion and then allowed to cool, the process is known as *fusion* or *autogenous* welding. The high localized temperatures required may be produced by (1) the heat of a flame of gas, usually acetylene, burning in a stream of pure oxygen, (2) the ignition of a mixture of iron oxide and aluminum (the thermit process), and (3) the use of the electric arc.

In welding with an oxyacetylene torch the oxygen and the acetylene are fed through a blowpipe and ignited at its tip. The flame has a temperature of approximately 5000°F. and a narrow strip of metal at the junction of the parts is fused, uniting the parts. Usually additional metal is added to the joint by melting in a small steel or iron rod. Wrought iron, steel, cast iron, copper, brass, aluminum, and numerous alloys of those metals are welded by the oxyacetylene process. Hydrogen and other fuel gases are sometimes used for welding, but acetylene is by far the most common gas used for that purpose. If an excess of oxygen is supplied to the torch it becomes a very effective cutting tool or, more correctly, a burning tool, for wrought iron or steel. In the presence of excess of pure oxygen heated iron or steel burns, and an oxyacetylene cutting torch burns a narrow gash when applied to a piece of steel or iron. The oxyacetylene cutting torch is widely used to cut up steel scrap and to cut small pieces of metal to approximate shape.

In the thermit process of welding a specially prepared mixture of aluminum and iron oxide is placed in a crucible and ignited. The heat of the resulting combustion raises the temperature of the mass to about 4800°F., and there is produced superheated melted iron which is poured around the joint to be welded, and which forms a solid casting at the joint.

In the electric arc process of welding, an arc is drawn between the metal to be welded and an electrode (usually a steel or iron rod) which is hand-operated. The heat of the arc melts the end of the electrode and also melts metal at the surfaces to be joined. The electric current supplied may be either direct or alternating.

Applications of Welding. Forge or hammer welding is used in the blacksmith-shop work on small pieces and, with special equipment, in the manufacture of tanks and pressure vessels. Plastic welding by the use of the electric current is essentially a manufacturing process and is used in the quantity production of small pieces and tanks.

Thermit welding finds its principal application in repair work on heavy sections, such as punch frames, and in welding rail joints.

Fusion welding, either by the oxyacetylene torch, or by the electric arc, is very widely used for general repair work and in many manufacturing processes. It is widely used in making large-size pipe and pressure vessels, such as oil stills and boilers, and for building up machine frames from rolled plates and shapes. It has come to be a rival of riveting in many kinds of structural-steel work and is used in the foundry for filling up small cavities in iron and steel castings, or for building up worn spots on a metal surface.

Special welding processes using gas fuel or electric current for heating

to a plastic state and then applying pressure to make the weld are in use for welding bars, tubes, small shapes, and railroad rails.

Common Defects in Welds. The commonest defect in a weld is the failure to make the welding complete over the cross section welded. The seams left by such incomplete welding can sometimes be detected by X-ray examination, and specifications for welded seams in high-grade pressure vessels usually require such examination.

Probably the best safeguard against defect is careful inspection of the welding process, and the occasional requirement that each welder make test joints for tensile tests by which his skill is to be rated. The use of welding machines in which the flame of the torch or of the arc is fed along the seam at a constant rate and at a constant distance from the surface produces more reliable welds that can be produced by handwork.

A second defect in welded joints is the presence of iron oxide. Two methods of preventing oxidation of the steel during fusion welding are in use. In one the arc, or the flame, is surrounded by a stream of dry hydrogen producing a nonoxidizing atmosphere around the weld, and in the other the same effect is produced by using welding rods coated with some material which, under the heat of the arc or the flame, will give off a nonoxidizing gas, such as carbon monoxide.

A third defect in welds is the presence of severe internal stresses left by uneven heating and cooling. These strains may be almost entirely relieved by reheating the welded article to a temperature somewhat below the critical temperature of steel (see page 138), and whenever feasible this should be done, especially when building up worn spots by welding.

Strength of Welds. Plastic welds if skillfully made form almost perfect joints. However, not all such welds are skillfully made, and, in general, it is not safe to count on more than 75 per cent of full strength for machine-made plastic welds, or for more than 50 per cent of full strength for ordinary forge or hammer welds.

Fusion welds are steel castings at the joint, and the crystalline structure is that of a steel casting rather than that of rolled steel. Fusion welds made on automatic welding machines under careful control and inspection frequently show as high strength under either steady or repeated loading, or as great energy resistance to impact, as the metal welded. However, the strength of the general run of field and repair shop fusion welds *cannot be counted on* for much more than half the strength of the metal welded.

POWDER METALLURGY

Definition. Powder metallurgy is the art of making objects (usually small) by the heat-treatment of compressed metallic powders, sometimes with the inclusion of nonmetallic material.

Outline of Process. Many metals, including several common structural metals, can now be obtained in the form of fine powder, which is produced by grinding, electrolysis, spraying of molten metal, or by the reduction of metallic oxides, the choice of method depending on the metal to be powdered. The powdered metal is then compressed in molds under very high pressure, varying from 10,000 to 200,000 lb. per sq. in., depending on the metal. By subsequent sintering, *i.e.*, heating to somewhat below the melting point, a fairly strong part is obtained.

Advantages of Powder Metallurgy. Proportions of different metals to be united can be fixed with a high degree of accuracy. Aggregates can be made between metals that have widely divergent melting points, such as copper and tungsten, or between metals and nonmetals such as copper, tin, and graphite. This last-named aggregate is widely used for "oilless" bearings, the graphite furnishing the lubricant. The dimensions of finished articles can be held to close tolerances, so that little or no machining is needed for the finished object. The heat-treatment may be conducted in a controlled atmosphere, so that contamination of the metal is prevented. The production in useful forms of the refractory metals like tungsten, molybdenum, and tantalum is at present possible by this method alone.

Limitations of Powder Metallurgy. The size of articles produced by powder metallurgy is limited by the size and cost of the press necessary to produce the high compressive pressures over a large surface. The tendency of some metals to stick to the die limits the depth of article that can be produced. In the case of some metals, air and moisture conditions of the room may make control of temperature and moisture necessary.

Although some articles produced by powdered metallurgy have shown as high strength as articles made from cast or rolled metal, the strength of the metals so produced can hardly be relied on to be more than 50 per cent of the strength of a similar article made of rolled metal (or alloy) of the same composition as that of the powdered aggregate.

Uses of Powder Metallurgy. Filaments of refractory metals, such as tungsten and tantalum; self-lubricating bearings consisting of an aggregate of a bearing metal (or alloy) and a lubricant (such as graphite); tungsten carbide tips for cutting tools; and iron alloys for permanent magnets are examples of articles made from powdered metal, or from powdered aggregate of metal and nonmetal. Small articles finished very closely to size can be made out of some metals whose melting point is too high to allow the use of die casting.

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Questions

1. Why is the surface condition of a machine or structural part more important if the part is subjected to bending or to torsion than if it is subjected to direct tension or compression?

2. Do fatigue cracks always start at the surface of a metal part? Are there any cases when they do not?

3. What are residual stresses?

4. Do you agree with the statement that a fatigue fracture in a metal part is preceded by slip within crystalline grains, but that not all such slipping results in fatigue cracks? Give reasons for your answer.

5. Sometimes the effect of the residual stresses in one direction (usually parallel to the axis of the piece) is regarded as the sole cause of the strengthening or weakening effect. Is this adequate reasoning? Explain.

6. If a fatigue crack starts as a slip along a plane of slip, why is it that fatigue fractures seem for the greater part of their length to follow a direction at right angles to the principal tensile stress?

7. State the general features of the carburizing process of surface strengthening. The general features of the nitriding process.

8. From the values given in Tables V(*B*) and XV determine whether the carburizing of 0.20 per cent carbon steel followed by oil quenching raised its endurance limit for 10,000,000 cycles of reversed bending up to the corresponding endurance limit for chrome-molybdenum steel.

9. From the values given in Tables V(*B*) and XVI, determine whether the nitriding of the metal increased its endurance limit for 10,000 cycles of reversed stress up to the corresponding endurance limit for oil-quenched chrome-nickel steel, drawn at 700°F.

10. What are the uses and the limitations of the flame-hardening process of surface treatment of steel?

11. Why is stress-relieving heat-treatment desirable after flame hardening?

12. Describe the process of induction hardening. What are its advantages and its limitations?

13. Explain the favorable results shown in Table XVII for those end-hardening processes for railroad rails that used a mild quench rather than a rapid quench.

14. Compare the resistance of anodic electroplating and of cathodic electroplating to corrosion in the base metal.

15. Is Alclad sheet metal stronger or weaker than the base metal, which is an aluminum alloy? Explain.

16. Why does hot-rolling produce stronger metal than merely casting? Why does moderate cold-working strengthen metal? What limits the increase of strength by this process?

17. Why is cold-working probably more effective on thin pieces of metal than on thick pieces? Why is cold-working effective in offsetting the effects of stress raisers, even on quite large pieces?

18. Compare the endurance limits found for cold-rolled 0.20 per cent carbon steel (item 5, Table XVIII) with the endurance limits for nickel steel given in Table V(*B*).

19. Discuss the residual stresses set up by the cold-rolling process shown in diagram in Fig. 65. Are these residual stresses permanent?

20. Describe the general process of shot peening. Examine the *S-N* diagrams in Fig. 67 and items 5 to 10 in Table XVIII, and state whether it seems to you that the rolling process or shot peening was the more effective in increasing endurance limits.

21. State the advantages and limitations of shot peening.

22. Discuss the cold-work done during polishing and machining of metals.

23. Describe briefly the process of ordinary forge welding, the thermit process, the oxyacetylene welding process, the electric arc-welding process, the electric flash-welding process with pressure, the gas-heat process with pressure.

24. What process of welding would you recommend for (1) a repair job on plate metal not over ½ in. thick in a town not supplied with electric power; (2) the manufacture of steel tanks; (3) the fabrication of the steel framework of a building; (4) the making of steel pipe; (5) the welding together of railroad rails; (6) the building up of worn places on machine parts?

25. State three defects frequently found in welds and tell what precautions, if any, can be used to safeguard against them.

26. Why are welded joints relatively weaker than the base metal under repeated loading than under steady loading?

27. Define powder metallurgy. Outline the general process used.

28. Discuss the advantages and the limitations of powder metallurgy.

29. Name several examples of parts that can be made of powdered metal.

30. Given two 3-in. diameter shafts, each with a ¼-in. keyway cut at each end. The shafts are made of hot-rolled mild steel. One of these shafts is subjected to a rapidly varying tensile load so that the calculated tensile stress varies from a low value of 5,000 lb. per sq. in. to a maximum of 25,000 lb. per sq. in. The second shaft is rotating with a constant bending moment applied to the shaft bearings so that the stress in the lowest part of the shaft is 15,000 lb. per sq. in. in tension. Analyze the

types of surface treatments which might be applied to the keyway in each shaft to help prevent fatigue failures. Which of the two loading conditions is the more critical? Which shaft will benefit the more by surface treatment?

31. Some fusion-welding techniques call for building up the weld metal between two members in several shapes or "passes." In this case, a layer of metal is deposited in the liquid condition, allowed to cool, and then, before depositing the next layer, it is peened with a special peening hammer and cleaned with a wire brush. Why is peening used? Why must the first layer of weld metal be cleaned before the next pass?

32. If a steel fusion weld is properly made, will it be stronger in tension than in compression? Explain.

33. Two flat pieces of steel are spot welded in the manner indicated in Fig. 69. Make a simple cross-sectional sketch of this joint, showing (*a*) the approximate path of the electrical current during the welding operation; (*b*) the region which was welded by fusion of the surrounding metal; and (*c*) regions which would be heated considerably, but *not* welded. Analyze the joint for stress concentration if a tensile load is applied to each of the flat pieces of steel.

CHAPTER XII

WOOD

Uses in Engineering Construction. Wood has been used as a structural material since the dawn of history. Today it is used because it is less costly than steel, concrete, brick, or stone. It is a lightweight material, can be handled with relative ease, and can be sawed and cut to almost any desired shape. On the other hand, it is subject to decay and attack by certain insects. This weakness in some ways corresponds to the weakness due to the corrosion of metals. Wood is easily inflammable but, even though charred on the surface, it will withstand considerable load, if burning progresses no further, while steel structural members would collapse under load if heated to red heat.

One weakness of wood as a structural material is its lack of *isotropy;* that is, its different resistance to stress in different directions. Practically all structural wood has a clearly marked grain (see Figs. 70 and 73). Wood is much weaker in tension and compression across the grain than along the grain, and is much weaker in shear along the grain than across the grain.

While wood does not have a high elastic strength or a high ultimate strength in tension or compression, it withstands a considerable amount of elongation or compression before it has suffered serious structural damage, and hence has a high resistance to the *energy* of stress and strain, as shown by the area under a stress-strain diagram carried to failure. This resistance to energy makes wood valuable for such structural parts as railroad ties or other parts subjected to the *energy* of shocks.

Supply, Production, and Consumption of Lumber in the United States. Estimates of the amount of standing timber in the United States, of the annual growth of timber, and of the consumption of timber are necessarily rough estimates, since the consumption of timber per annum changes rapidly. Damage by fire and by insects is being lessened by improved methods of fire protection and extermination of damage-producing insects. Planting of timber-bearing trees is on the increase, and increased use of steel and brickwork somewhat diminishes the demand for timber.

Estimates of the annual growth and the annual consumption of timber indicate that at present the annual consumption is about three

times the annual growth. This is less than the ratio of four times the annual growth made in 1942.

Table XIX shows a rough estimate of the percentage of the wood which is consumed annually in the United States, including the various uses and losses. The total annual consumption is estimated at about 90,000,000,000 board feet. Table XX shows an estimate of the percentages of soft wood and of hard wood produced by various regions in the United States.

TABLE XIX. ESTIMATED ANNUAL CONSUMPTION OF TIMBER IN THE UNITED STATES (1949)

Estimated standing timber in the United States	1,764,000,000,000 bd. ft.
Estimated annual growth of timber in the United States	32,000,000,000 bd. ft.
Estimated annual consumption of timber in the United States	90,000,000,000 bd. ft.

Use and loss of timber	Per cent of total consumption in U. S.
Construction and planing mill products	20.6
Boxes and crates	5.0
Railroad ties	5.3
Mine timbers	2.0
Furniture, vehicles, lath, veneer, agricultural implements, poles, ship timber	8.3
Fuel	23.1
Posts and fencing	6.7
Pulpwood	9.0
Losses by fire and insects	20.0

TABLE XX. APPROXIMATE PERCENTAGE OF LUMBER FURNISHED ANNUALLY BY DIFFERENT REGIONS IN THE UNITED STATES

Region	Lumber furnished, per cent of production of the U. S.
SOFTWOOD	
Western (Wash., Ore., Calif., Rocky Mountains)	42
Southeastern (Va., N. C., S. C., Ga., Fla., Ala., Miss., Ark., La., and extreme Eastern part of Tex., Okla. and Kan.)	40
Northeastern (New England, N. Y., Penn., N. J., Del. Md.)	6
Central (Ohio, Ind., Ill., Ken., Tenn., W. Va.)	4
Great Lakes (Mich., Wis., Minn.)	8
HARDWOOD	
Southeastern	50
Central	20
Great Lakes	16
Northeastern	14

The states of North Dakota, South Dakota, Kansas, Oklahoma, and Texas furnish relatively small crops of lumber. The states of the Rocky Mountain region and of the Pacific Coast region furnish relatively small crops of hardwood lumber

It should be noted that the figures given in this chapter do not make any allowance for the lumber in the Canadian forests. The annual consumption of timber in the United States is still greater than the annual growth of timber, but the ratio of consumption to growth has been diminished in recent years, and considering the forests of both the United States and of Canada, there seems reason to hope that the lumber industry still has a good chance of a long life.

Principal Varieties of Structural Timber. The commercial varieties of wood are divided into two general classes, softwood and hardwood. The distinction between hardwood and softwood is not entirely logical. Some of the harder and stronger of the "soft" woods (*e.g.*, southern pine) surpass in hardness and strength the softer species of "hard" wood (*e.g.*, poplar). The term softwood is applied to wood from any one of the numerous cone-bearing trees, of which the pines, the spruces, the hemlock, the fir, the tamarack, the cedar, the cypress, and the redwood are the principal species. Nearly all cone-bearing trees are "evergreens." The term hardwood is applied to wood from the "broad-leaved" trees, some of the commonest of which are the white oak, the red oak, the ash, the hickory, the poplar, the maple, the walnut, the chestnut, the beech, the catalpa, the eucalyptus, and the mahogany. For general structural purposes the softwoods are much more generally used than are the hardwoods. The principal uses of the hardwoods are for interior finish, furniture, cabinet work, and the like, though white oak and red oak are used for railroad ties, and hickory and ash are used for the wooden parts of vehicles and agricultural implements. Table XXI gives the characteristics and the uses of the more common kinds of wood.

Logging. The first step in the production of commercial lumber from standing timber is "logging"—that is, the cutting down of trees in the forest, trimming off branches and vegetation, cutting the trunks and limbs to sizes which can be handled, and transporting the resulting logs to the sawmill. Methods of felling trees and of transporting logs vary widely according to local conditions. Logging is usually carried on in the winter. During the late fall and winter, wood is freer from sap and, if cut in that condition, decays less rapidly than if cut in the spring or early summer when the sap is more plentiful. At the sawmill the logs are sawed into the commercial sizes of lumber, either by rotary saws or by band saws. Poles and posts, and some railway ties, are usually hewed to shape rather than sawed.

Seasoning of Timber. The high moisture content of green timber is reduced by exposure to the atmosphere or by heating in kilns. The former process is called seasoning and it reduces the moisture content from about 32 to about 13 per cent. During the period of seasoning, timber

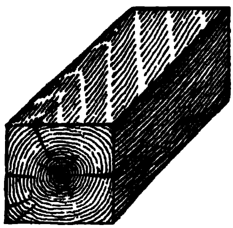
TABLE XXI. CHARACTERISTICS AND USES OF NORTH AMERICAN WOODS

Species	Characteristics	Uses
Soft woods:		
Southern pine	Heavy, hard, strong, tough, coarse-grained, decays in contact with soil	Heavy framing timbers, flooring
White pine	Light, soft, straight-grained, not very strong	Pattern making, interior finish
Norway (red) pine	Light, hard, coarse-grained	All kinds of construction
Western pine	Trade name for a number of kinds of wood, general characteristics somewhat like Norway pine	General construction work
Douglas fir (Oregon fir)	Hard, strong, wide variations in quality, durable, rather difficult to work	All kinds of construction
Eastern hemlock	Soft, light, brittle, splits easily, not durable	Cheap framing timber, boxes and crates
Western hemlock	Stronger than Eastern hemlock	Same as Eastern hemlock
Tamarack (larch)	Hard, heavy, strong, durable	Posts, poles, ship timbers, ties, sills
Spruce	Light, soft, close-grained, straight-grained, resists decay and marine boring insects	Framing timbers, piles, underwater construction
Cedar	Soft, light, fine-grained, very durable	Water tanks, shingles, posts, fencing, boat building
Redwood	Light, soft, weak, brittle, coarse-grained, straight-grained, easy to work, durable in contact with soil	Ties, posts, poles, general construction work
Cypress	Very durable, light, hard, close-grained, easily worked, takes high polish	House siding, shingles, poles, building lumber, interior finish
Hard woods:		
White oak	Heavy, strong, tough, close-grained, splits with difficulty, checks if not carefully seasoned, takes high polish	Framed structures, interior finish, ties, vehicle and furniture making
Red oak	Softer, weaker, and more porous than white oak	Ties, furniture. interior finish
Hickory	Heaviest, hardest and toughest of North American woods. Attacked by boring insects	Vehicles, handles, agricultural implement manufacture
Maple	Heavy, hard, strong, coarse-grained. Takes good polish	Flooring, interior finish, furniture
Ash	Heavy, hard, brittle, "springy"	Interior finish and cabinet work
Elm	Heavy, hard, strong, tough, very close-grained, difficult to split and shape, warps badly	Vehicle and ship building, sills

should be piled so that air has free access to each stick. The time required for proper seasoning varies widely for different kinds of wood and for different sized pieces, but is never less than several weeks. Hardwood is usually seasoned several months before being kiln-dried. Kiln-drying of timber is carried on at a temperature of 158 to 180°F. Kiln-drying

reduces the moisture content of timber to about 3.5 per cent. If the timber is allowed to get too hot, chemical changes take place in the wood structure which reduce the strength and the toughness of the wood.

Shrinkage of Wood during Seasoning. During the seasoning of wood, shrinkage takes place and the circumferential shrinkage in a stick is greater than the radial shrinkage. This is partly due to the resistance to radial shrinkage offered by the rays of the wood, partly to the reduction of shrinkage of the rings of summer wood on account of the smaller shrinkage of spring wood, while the summer wood shrinks circumferentially along the rings. The effect of this uneven shrinkage is to set up



(a) Cracks.

(b) Warping.

Fig. 70. Defects in wood caused by too rapid seasoning or kiln-drying.

internal stresses, which sometimes cause cracks or checks in wood (see Fig. 70).

In sawing boards from a log of wood, boards sawed tangent to the annual rings are known as "plain-sawed" lumber in hardwoods, and as "flat-grain" or "slash-grain" lumber in 50-ft. woods; boards sawed parallel to the radius of the log or to the "rays" in the wood are known as "quarter-sawed" lumber in hardwoods and as "edge-grain" or "vertical grain" lumber in softwoods.

The quarter-sawed or edge-grain lumber is usually not quite parallel to the radius of the log and often the surfaces at the edges of the plain-sawed boards are not very near to tangency to the annual rings. In commercial practice it is common to call material with rings from 0 to 45 deg. with the surface quarter-sawed, while material with rings from 45 to 90 deg. is called plain-sawed. Figure 71 shows a quarter-sawed board and a plain-sawed board cut from half of a circular log.

Advantages of plain-sawed lumber. (1) It is usually cheaper, because its cutting requires less time and involves less waste; (2) round or oval knots occur in plain-sawed boards, and they affect the strength less than the spike knots which occur in quarter-sawed boards; (3) "shakes" (see page 184 for definition) and pitch pockets when present extend

through fewer boards; and (4) it does not collapse so easily on drying as does quarter-sawed lumber.

Advantages of quarter-sawed lumber. (1) It shrinks and swells less in width; (2) it twists and cups less; (3) it does not surface check or split so badly in seasoning and in use; (4) it wears more evenly; (5) it does not allow liquids to pass into it or through it so readily; (6) it holds paint better in some species; (7) the width of sapwood appearing in a quarter-sawed board is limited according to the width of the sawwood in the log.

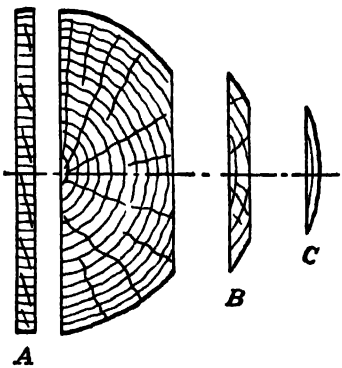


Fig. 71. Boards cut from log. (*A*) Quarter-sawed (edge-grained). (*B*) Plain-sawed (flat-grained). (*C*) Slab.

Classification and Grading of Lumber. Various lumber associations for hardwood and for softwood classification and grading have published standards for lumber. These classifications and gradings change from time to time, so that no data can be given here which would meet the classification and the grading of future years. At the present time, reference to the current "Standards" of the A.S.T.M. (the 1949 edition and the 1951 supplement at the time of this writing) and publications of the U. S. Forest Service are reliable sources of information.

In a general way, then, a few paragraphs on classification of softwood lumber are given to show the type of classification and grading which is applied to lumber, rather than to give precise values for use at the present time or in the future.

Classification of Softwood Lumber (Based on "Simplified Practice Recommendation 16," second revision, U. S. Dept. Commerce). Lumber is the product of the saw and planing mill, not further manufactured than by sawing, resawing, and passing lengthwise through a standard planing machine, crosscut to length, and matched.

Use Classification. *Yard Lumber.* Lumber that is less than 6 in. in thickness and is intended for general building purposes.

Structural Timbers. Lumber that is 6 in. or over in thickness and width.

Factory or Shop Lumber. Lumber intended to be cut up for further manufacture.

Size Classification. *Strips.* Yard lumber less than 2 in. thick and under 8 in. wide.

Boards. Yard lumber less than 2 in. thick, 8 in. or over in width.

Dimension Lumber. All yard lumber except boards, strips, and timbers; that is, yard lumber not less than 2 and under 7 in. thick and of any width. This includes (1) planks, yard lumber not less than 2 and under 4 in. thick and 8 in. and over in width; (2) scantlings, yard lumber not less than 2 and under 6 in. thick and under 8 in. wide; (3) heavy joists, yard lumber not less than 4 and under 6 in. thick and 8 in. or over in width.

Timbers. Lumber 6 in. or larger in smallest dimension.

Manufacturing Classification. *Rough Lumber.* Undressed as it comes from the saw.

Surfaced Lumber. Lumber that is dressed by running through a planer. It may be surfaced on one side ($S1S$), two sides ($S2S$), one edge ($S1E$), two edges ($S2E$), or a combination of edges and sides ($S1S1E$), ($S2S1E$), ($S1S2E$), or ($S4S$).

Worked Lumber. Lumber which has been run through a matching machine, sticker, or molder. Worked lumber includes (1) matched lumber, which is edge dressed and shaped to make a close tongued and grooved joint at the edges or ends when laid edge to edge or end to end; (2) shiplapped lumber, which is edge-dressed to make a close rabbeted or lapped joint; (3) patterned lumber, which is shaped to a patterned or molded form.

Grade Standards for Softwoods. The Simplified Practice Division of the U. S. Bureau of Standards and various technical societies recognize two general grades for softwood lumber: *select* and *common* lumber. Various subdivisions of these grades are recognized for special services. In general, lumber that is clear, containing defects limited both as to size and number (usually by definite specification for any particular service), and that is smoothly finished and suitable for use for finishing purposes or other uses in which large, clear pieces are required, is considered as *select lumber.*

Lumber containing defects or blemishes sufficiently serious to preclude its use for finishing purposes, but which is suitable for general utility and construction purposes, is considered as *common lumber.*

Defects in Lumber. Some of the common defects found in commercial lumber are cross-grain, knots, splits and cracks (called "shakes"), bark or raggedness at the edges of boards (called "wane"), and pitch pockets. "Ring shakes" are cracks between the annual rings of wood; "through shakes" are cracks extending between two faces of a piece of lumber; and "unsound" knots include loose knots and rotten knots (knots softer than the surrounding wood). Pitch pockets are openings between the fibers of the wood, extending along the grain, and containing pitch or bark. "Rot," "dote," and "red heart" are names given to any form

of decay which may be evident either as a dark red discoloration not found in the sound wood, or as white or red rotten spots.

The injurious influence of a knot is determined by its location in a piece of lumber and by the area of cross section it occupies. Knots in posts and heavy beams, which are likely to show only on one face or to run diagonally through the piece, reduce the strength in practically direct proportion to their size as measured. Knots along the edges of planks are more injurious than knots along the middle part of the width. In joists and beams knots reduce the strength most if located along the top and bottom edges through the central portion of the length. On the top or bottom of a beam the injurious influence is measured largely by the surface fibers cut. The distortion of grain around a large knot is proportionally greater than around a small knot.

Shakes reduce the area of a beam acting in resistance to shear. Wane is limited by such considerations as bearing area, nailing edges, and appearance rather than by effect on strength. Pitch pockets are ordinarily not regarded as defects in structural lumber. However, a large number of pitch pockets indicates a general lack of bond between fibers of wood, and a piece of lumber containing many pitch pockets should be carefully inspected for shakes.[1]

Structure of Wood. A tree grows by the annual addition of consecutive rings of wood fiber. The growth takes place on the outside rings. A cross section of a tree shows a central core or "pith" of small diameter which assists the tree growth by storing up plant food during the first year or two. Outside this pith are concentric rings, usually well marked, which show the growth of the tree from year to year. The width of these rings varies widely in different species of trees, and in different trees of the same species grown under different conditions. The width of rings is a function of the rate of growth of the tree. The outer rings of a mature tree serve as ducts for the passage of sap, which furnishes the plant food necessary for the growth of the tree, and the wood of the outer rings is called sapwood (Fig. 72). The inner rings have ceased to carry sap, and the wood from the inner rings is called heartwood.

In the temperate zone the rate of growth of a tree varies greatly for different seasons of the year. The growth is most rapid in spring, less rapid in summer and early fall, and practically zero for late fall and

[1] The above notes on defects are summarized statements from the "U. S. Forest Products Laboratory Notes on Working Stresses." The complete statement of these notes on defects, and specifications for structural wood joists, planks, beams, stringers, and posts, form a part of the American Lumber Standards, and may be found in Part 4, pp. 579–738, of the 1949 "Standards" of the A.S.T.M.

winter. The "spring wood" is usually lighter colored than the "summer wood" and the annual rings of a tree usually appear distinct on account of the juxtaposition of the dark-colored summer wood and the light-colored spring wood of the next year's growth.

The softwoods are made up for the most part of an aggregation of elongated tubular cells (tracheids) which extend in a direction parallel to the axis of the tree trunk. These cells are closed at the ends and absorb water through their porous walls. At right angles to these tubular cells are numerous groups of cells extending in a radial direction and called rays. Through these rays plant food is distributed across the tree section. In some softwoods there are longitudinal tubes called resin ducts, in which resin is formed.

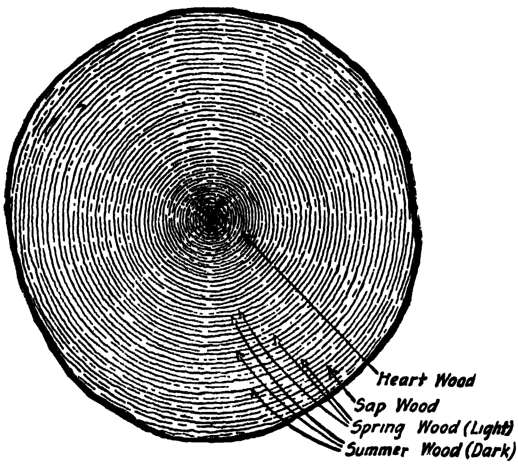


FIG. 72. Cross section of tree showing annual rings.

The hardwoods have a much more complex structure than the softwoods. In hardwoods the rays are much larger and more numerous than in softwoods. The elongated tubular cells (tracheids) are of minor importance, and the principal structural elements of the hardwoods are longitudinal wood fibers, made up of elongated, sharp-pointed cells with very thick walls.

The general longitudinal direction of the tubular cells which make up the greater part of wood gives a distinctive "grain" to its structure. If these cells extend parallel to the axis of the tree trunk, the timber from the tree is straight-grained, if the fibers take a spiral course the grain is twisted, and if the "sense" of the spiral (right-handedness or left-handedness) is reversed as the tree grows, the timber is cross-grained. Figure 73 shows examples of straight-grained, twisted-grained, and cross-grained timber.

When, during the growth of a tree, the trunk end of a branch becomes enclosed by successive annual rings, there is formed a knot in the wood. Knots sometimes constitute serious defects in timber (see page 185).

Strength of Wood. The strength of timber is affected by a great many factors, and for timber structures, the safe working stresses are very much lower than the ultimate as shown by laboratory tests of specimens; in other words, it is necessary to use a high "factor of safety" for timber. One of the factors which influence the strength is the "grain" of wood. The tensile strength and the compressive strength in a direction parallel to the grain (along the grain) are much higher than in a direction perpendicular to the grain (across the grain). The shearing strength along

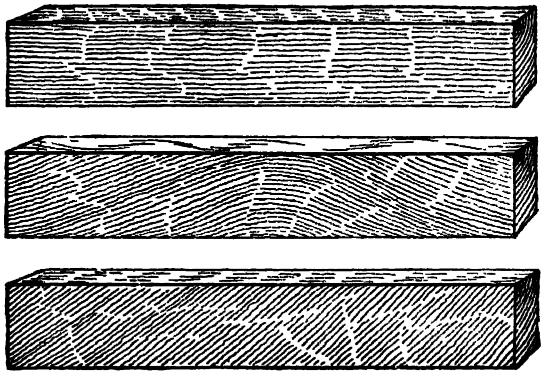


FIG. 73. The "grain" of wood. Upper stick is straight-grained, lower two sticks show cross-grained or twisted-grained wood.

the grain is much lower than the shearing strength across the grain. The shearing strength of timber along the grain is very much lower than the tensile or compressive strength along the grain, and this fact must be kept in mind when the strength of timber beams is being considered. For this reason the horizontal shear in timber beams is a much more important factor than it is in steel beams, and it should always be taken into account in designing a timber beam. Figure 74 shows a characteristic failure of a beam by horizontal shear. The low strength along the grain makes it difficult to use wood for tension members of structures. Figure 75(*a*) shows a stick of timber in tension held at the ends by bolts through the stick. For this stick there is danger of failure by shear along the lines *ac* and *bd* rather than by tension on a cross section of the stick. To develop the tensile strength of the cross section it would be necessary to have very long ends. Figure 75(*b*) shows a joint between two timbers. The danger of failure by shear along *mn* must be considered, as well as the compressive stress on *nq*.

The tensile strength of timber is important chiefly in the consideration of tensile stresses in timber beams.

TABLE XXII. EFFECT OF SLOPE OF GRAIN OF WOOD ON STRENGTH
Based on test data obtained at U. S. Forest Products Laboratory, Madison, Wis.
(see reference 1 at end of this chapter)

For beams		For posts or columns	
Slope of grain with respect to direction of stress	Reduction in strength, per cent	Slope of grain with respect to direction of stress	Reduction in strength, per cent
Up to 1 in 40	Negligible	Up to 1 in 40	Negligible
1 in 20	12.5	1 in 15	12.5
1 in 15	25.0	1 in 11	25.0
1 in 11	37.5	1 in 8	37.5
1 in 8	50.0	1 in 6	50.0

The effect of the slope of grain on the strength of the wood may be estimated from the values in Table XXII, which is based on test data and recommendations of the U. S. Forest Products Laboratory.

Timber is good material for compression members. In trusses for roofs and bridges a combination of steel for the tension members and

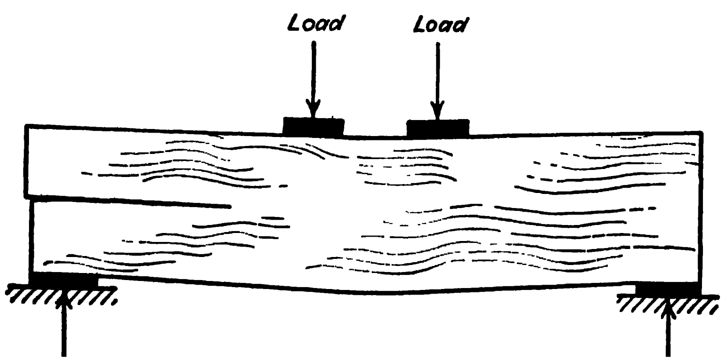


FIG. 74. Failure of wood beam by horizontal shear. Shear crack can be seen extending along the beam at about mid-depth.

wood for the compression members is sometimes used. Timber is very rarely used for shear members or for torsion members. Table XXIII gives average values for the strength of various kinds of wood, as determined by laboratory tests.

Strength of Wooden Columns. Extremely long columns of any material under compressive load fail not by crushing but by sidewise buckling. Very short columns fail by crushing of the material, or sometimes by diagonal shearing, or, in rare cases, under circumferential tensile strain. Columns of intermediate length fail by a combination of crushing and buckling. The limiting ratio of length of column to minimum transverse dimension is a function of the ratio of modulus of elasticity E of the material to its crushing strength. For wood this ratio is low and the limiting length at which wooden columns tend to buckle rather than to fail by crushing is relatively low.

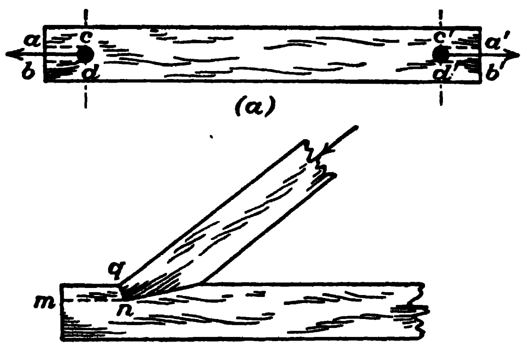


FIG. 75. Wooden structural parts under stress.

In the "Wood Handbook" of the U. S. Forest Products Laboratory at Madison, Wis., wooden columns are divided into three classes:

1. Columns in which the ratio of column length L in inches to the shortest side of a rectangular column or the diameter of a circular column d in inches is not greater than 11.

2. Columns in which L/d is greater than 11, but not greater than K. K is the value of L/d above which the column fails by buckling rather than by crushing. Such a failure is called an "Euler" failure of a column, and the Euler formula for column strength applies. Using a factor of safety of 3 for wooden columns, the "Wood Handbook" gives the equation $K = 0.64\sqrt{E/S}$, in which E is the modulus of elasticity of the wood in compression, and S is the safe working stress for compression parallel to the grain of the wood.[1]

3. In columns having an L/d greater than K, the Euler formula is recommended.

Using a factor of safety of 3 the safe value of the average compressive load on the column P/A (P in pounds and A in square inches) is as follows:

[1] Values of S and E for wood are given in Chap. VII, Table XI.

TABLE XXIII. STRENGTH OF WOOD

Recommended *working stresses* for wood and values of modulus of elasticity are given in Table XI, Chap. VII. This table gives average values for elastic ultimate strength of various species of wood under different conditions as to moisture and size of specimen. The values are based on data reported by the Forest Products Laboratory in the U. S. Department of Agriculture *Bulletin* 556, and on data reported by the Materials Testing Laboratories of the Universities of Illinois and California. For small pieces of wood, which can be very carefully selected (such as wood for airplane construction), higher strength values can be obtained

Species of wood [1]	Weight (dry), lb. per cu. ft.	Strength, lb. per sq. in.					
		Cross-bending		Compression parallel to grain		Compression across grain	Shear parallel to grain
		Yield [4] strength	Modulus of rupture (computed stress at ultimate)	Yield [4] strength	Ultimate	Yield [4] Strength	Ultimate
1. Soft wood, full size structural timber with ordinary defects, green [2]							
Southern pine	34	3,800	4,600	2,800	3,300	440	360
Douglas fir	28	3,900	4,300	2,500	4,400	430	310
Norway pine and white pine [1]	24	2,800	4,100	2,000	2,800	350	190
Hemlock (eastern)	28	2,900	4,300	3,200	3,900	320	200
Tamarack	31	2,500	3,700	2,200	2,900	300	200
Redwood	22	2,300	2,600	2,200	2,900	350	170
Spruce	24	2,500	3,600	2,300	3,000	430	190
Cedar	23	2,800	3,400	2,000	2,600	380	130

2. Soft wood, small, clear test specimens, air-dry (12 per cent moisture content) [3]							
Yellow pine	34	6,600	11,000	4,100	5,800	900	800
Douglas fir	28	6,700	10,400	3,800	5,000	800	500
Norway pine and white pine	24	6,400	7,900	3,800	5,400	700	400
Hemlock	28	6,300	10,400	4,600	5,400	600	400
Tamarack	31	7,600	13,100	3,700	4,800	700	400
Redwood	22	4,800	7,800	3,900	5,100	560	330
Spruce	39	8,400	10,000	5,700	7,300	700	800
Cedar	23	5,800	6,300	4,000	5,200	700	400
Cypress	29	6,600	7,900	.....	6,000	800	550
3. Hard wood, small, clear test specimens, air dry (12 per cent moisture content) [3]							
White oak	50	9,600	13,100	5,000	8,500	2,200	1,000
Red oak	45	9,200	11,400	4,500	7,200	2,300	1,100
Hickory	50	11,500	16,000	5,500	10,000	2,700	1,150
Ash	39	7,900	10,800	4,000	6,000	1,900	1,100
Elm	34	7,300	10,300	5,500	6,500	1,200	800
Maple	43	5,000	7,000	5,500	8,000	1,300	500

[1] The wood marketed as western pine includes several species. It has about the same average strength values as white pine.

[2] For all large structural timber except pieces very carefully dried and protected from reabsorption of moisture test values for green timber should be used. For the rare cases where air-dry timber is used, and can be kept in an air-dry condition the strength values will be increased about 50 per cent above those given.

[3] For most small pieces of timber it is possible to use air-dry wood and to keep it in that condition. For small pieces which are liable to reabsorb moisture the values given will be diminished by about 33⅓ per cent. For the rare cases where kiln-dry wood can be used and protected from reabsorption of water the values given will be increased about 33⅓ per cent.

[4] Yield strength taken at a deviation from straight-line stress-strain diagram of approximately 0.05 per cent strain, see p. 23.

For Class 1 (L/d not greater than 11),

$$\frac{P}{A} = S$$

For Class 2 (L/d greater than 11 but not greater than K),

$$\frac{P}{A} = S\left[1 - \frac{1}{3}\left(\frac{L}{Kd}\right)^4\right]$$

For Class 3 (L/d greater than K) the Euler formula in this form is

$$\frac{P}{A} = \frac{0.274E}{(L/d)^2}$$

Columns of Circular Cross Section. The above formulas may be used directly for rectangular columns (including square columns). To

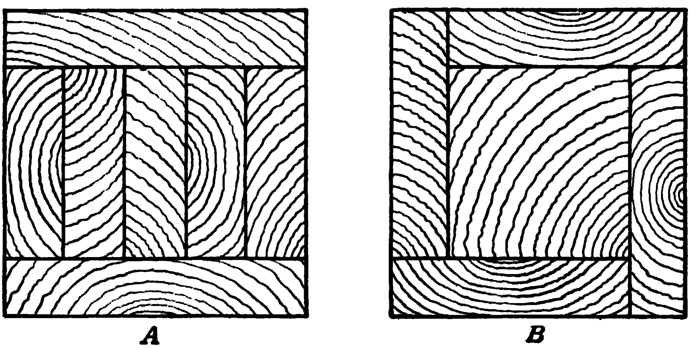


FIG. 76. Two types of built-up columns. (A) Edges tied together with cover plates. (B) Boxed solid core. (*Courtesy of U.S. Forest Products Laboratory, Madison, Wis.*)

compute the required size of a round column, design first for a square column and then compute the circular column with a diameter d that gives an area equal to that of the square column. If the column is tapered, the diameter to use should be taken at two-thirds the length from the large end. The compressive stress at the small end should also be computed to make sure that there is no danger of crushing by the stress at the small end.

Laminated Wooden Columns. Two types of laminated wooden columns are shown in Fig. 76. In column A several pieces are spiked face to face and their edges are tied together with cover plates; in column B four planks are boxed around a solid core.

Laminated columns are not as strong as solid columns of the same material and of the same over-all dimensions. The percentage of

solid-column strength for different values of L/d may be estimated by interpolation in the following tabulation, which is that given in the revised 1940 edition of the "Wood Handbook," slightly modified.

L/d ratios	Per cent of solid-column strength
Up to 11	75
14	71
18	65
22	74
26	82

It will be noted that the minimum percentage of solid-column strength is for L/d of about 19, which has a percentage value of about 64. This decrease of strength followed by an increase may be explained as due to the varying combination of crushing and buckling up to slightly less than a value of K, with increasing percentage when the crushing action becomes relatively smaller and the buckling action relatively larger.

The "Wood Handbook" does not give different formulas for fixed-end and pivot-end columns of wood. Wood deforms elastically much more than the structural metals and it is very difficult to design a wood column which would not yield enough to fall short of fixed-endedness.

Elastic Properties of Wood. Wood has no yield point. The yield-strength stress at about 0.05 per cent strain deviation (offset) from a straight-line stress-strain diagram furnishes a good criterion of elastic strength; values of the yield strength for various kinds of timber are given in Table XXIII. Table XI, Chap. VII, gives values of the modulus of elasticity for timber.

Wood is a good material for structural members and machine parts which must withstand shock, such as railway ties, fence posts, spokes and rims of wheels, and hammer handles. The reason for this is the fact that resistance to shock depends on two factors: (1) the stress which can be carried without failure, and (2) the deformation (stretch, compression, bending, twisting) which can be withstood. Wood cannot withstand a high stress without injury, but can withstand a very large deformation without injury. The *elastic* resistance to impact (resilience) for any material is measured by the energy which can be recovered on release of the yield-strength stress. Figure 77 shows a stress-strain diagram for wood up to the yield strength, and the energy of recovery per cubic inch of material is measured by the shaded area MNR. MN is the stress-strain line for release of the yield-strength stress S_y, and it is very closely parallel to the line OP, whose slope measures the

modulus of elasticity of the material (E). Hence $NR = S_y/E$. And denoting the resilience[1] (recoverable energy) per cubic inch by V_y,

$$V_y = \frac{1}{2} S_y(NR) = \frac{1}{2} S_y \frac{S_y}{E} = \frac{S_y^2}{2E}$$

An examination of stress-strain diagrams for wood, cast iron, and steel shows that for elastic resistance to shock, wood has a lower capacity per cubic inch than steel, and a much higher capacity per cubic inch for elastic resistance to shock than does cast iron. Wooden parts for structures and machines have, in general, ten or twelve times the volume of steel or cast-iron parts, in order to resist the stresses set up, and as shock-resisting capacity of a member is proportional to the product of its volume and the shock-resisting capacity per cubic inch of the material, wooden structural members have a higher capacity for elastic resistance to shock than do steel members, and a very much higher capacity than do cast-iron members.

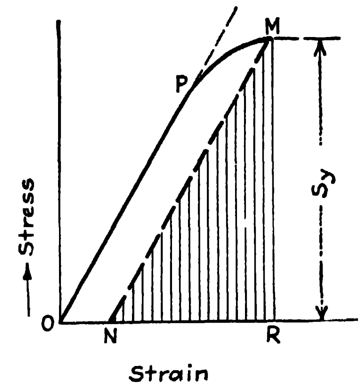


FIG. 77. Elastic resilience of wood.

In resistance to complete rupture under shock, wood ranks higher than does cast iron, but lower than structural steel. Resistance per cubic inch of material to complete rupture under shock is measured by the area under the entire stress-strain diagram.

Strength of Large Pieces of Timber. In using the values of ultimate strength given in Table XXIII as the basis from which to determine allowable working stresses for full-sized wooden structural members, the effect of size of member must be considered. If the structural member is small, *e.g.*, a rod for the frame of an airplane, and a selected piece of clear, straight-grained timber can be used, the values for ultimate strength given in Table XXIII for small, clear test specimens could be developed. For a large structural member of the same kind of wood, *e.g.*, for a bridge stringer, the probability of knots, cross-grained wood, and other defects would be high, and the ultimate stress would be that given for full-sized structural timbers. Tests of large timber beams and columns always give lower results for ultimate stress than do tests

[1] Attention is called to the fact that some writers define resilience as the energy required to produce a given stress in a material. According to this definition (which is not used in this book) the elastic resilience would be measured by the area $OPMRN$ in Fig. 77.

of small selected specimens of the same kind of wood. Table XI, Chap. VII, gives working stresses for various kinds of timber which have come to be considered safe by engineers.

Effect of Moisture on the Strength of Timber. Structural timber as ordinarily placed on the market contains about 12 per cent of water. If the timber has been kiln-dried, the moisture content is reduced to about 3.5 per cent. Green timber may have as high a moisture content

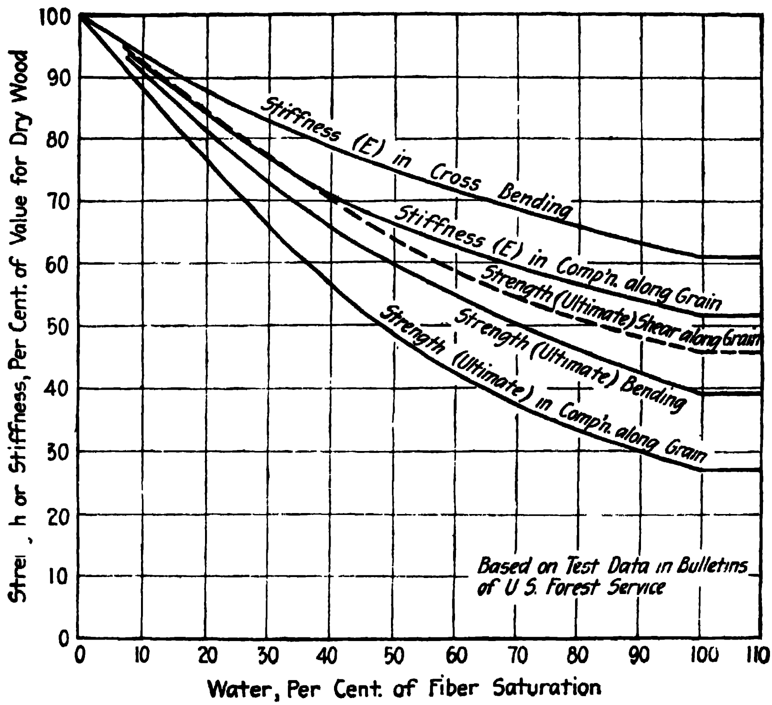


FIG. 78. Effect of moisture on strength and stiffness of softwood. For softwood, fiber saturation occurs at a moisture content averaging about 25 per cent.

as 35 per cent. Up to a moisture content of about 25 per cent the fibers of the wood absorb water and are softened and weakened by it, especially in compression. Above this saturated condition, which is called the "fiber saturation point," water no longer affects the strength and stiffness of wood. The general effect of moisture content on the strength and the stiffness of softwood is shown by Fig. 78, the basis of which is found in the results of tests by the U. S. Forest Service, made principally by H. D. Tiemann. As an illustration of the use of Fig. 78, consider the flexual strength of wood which, when in a green or saturated condition, has a moisture content of 25 per cent. If such wood is air-

dried until its moisture content is reduced to 12 per cent, it is then $^{12}/_{25}$ or 48 per cent saturated, and its flexural strength will be increased to about $^{60}/_{39}$ or 154 per cent of its strength green. If it is kiln-dried until its moisture content is reduced to 3 per cent, it will be $^{3}/_{25}$ or 12 per cent saturated and its flexural strength will be increased to about $^{90}/_{39}$ or 231 per cent of its strength green.

Moisture affects the strength of structural timbers both directly and indirectly. The direct effect of loss of moisture is the stiffening and strengthening of the wood fibers. This increase in strength, however, is accompanied by checking, splitting, warping, and twisting; as a consequence, some of the strength due to drying is lost. Timbers are also subject, during use, to varying conditions of moisture, from the dry location in a heated building, to the continually wet condition of some pier and dock timbers. All of these conditions are taken into account in recommending working stresses under different conditions of use.[1]

Time Element in the Strength of Timber. Under long-continued static loads timber will fail under stresses much lower than the ultimate stresses found by laboratory tests, in which the loading extends over a few minutes, and will take a permanent set at loads below failure. This time effect extends over several months, if not over longer periods of time, for large pieces of timber. Under long-time loading, test pieces of timber have been broken under stresses a little greater than 50 per cent of the ultimate strength as given by short-time tests. If it is important to minimize sag in wooden structures designed for long service, it is advisable to use working stresses half as great as those given in Table XI, Chap. VII. This very pronounced time effect is one of the reasons why working stresses for timber are so low as compared with the ultimate strength as determined by tests in a testing machine.

Relation of Strength and Shrinkage of Timber to Density. An examination of a large number of test results, made by Newlin and Wilson of the U. S. Forest Service, has established fairly definite relations between the strength and the shrinkage properties of wood and its specific gravity. In their investigation they determined the specific gravity as the ratio of the weight of a specimen of wood *oven-dry* to the weight of a volume of water equal to the volume of the specimen *at the time of testing.* Calling this ratio G the following equations give the shrinkage in per cent from green condition to oven-dry condition.

Shrinkage in volume, per cent $= 28\,G$.

Shrinkage in radial dimensions, per cent $= 9.5\,G$.

Shrinkage in tangential dimensions, per cent $= 17.0\,G$.

[1] From U. S. Forest Products Laboratory notes.

Table XXIV gives the relations of strength values established by the study of test data.

Veneer, Plywood. Owing to the increasing cost of hardwood there has been developed the use of boards of softwood with very thin sheets of hardwood glued on. These thin sheets are known as veneer, and have been very commonly used to give a hardwood surface to cheap

TABLE XXIV. RELATION OF STRENGTH OF WOOD TO ITS SPECIFIC GRAVITY

Based on the investigation of Newlin and Wilson of the U. S. Forest Service (see *Bulletin* 676, U. S. Dept. of Agriculture). G is the specific gravity of the wood, based on the weight oven-dry and the volume at the time of test and in the condition when tested.

Strength property	Green wood	Air-dry wood
Static flexure:		
Yield strength, lb. per sq. in.	$10,300\sqrt[4]{G^5}$	$19,000\sqrt[4]{G^5}$
Modulus of rupture, lb. per sq. in.[1]	$18,500\sqrt[4]{G^5}$	$26,200\sqrt[4]{G^5}$
Modulus of elasticity, lb. per sq. in.	$2,500,000\ G$	$3,000,000\ G$
Impact flexure with 50-lb. hammer unit stress at:		
Yield strength, lb. per sq. in.	$23,500\sqrt[4]{G^5}$	$35,000\sqrt[4]{G^5}$
Modulus of elasticity, lb. per sq. in.	$3,000,000\ G$	$3,550,000\ G$
Compression parallel to grain:		
Yield strength, lb. per sq. in.	$6,800\sqrt[4]{G^5}$	$11,000\sqrt[4]{G^5}$
Stress at ultimate, lb. per sq. in.	$6,900\ G$	$12,000\ G$
Modulus of elasticity, lb. per sq. in.	$2,860,000\ G$	$3,500,000\ G$
Compression perpendicular to grain:		
Yield strength, lb. per sq. in.	$2,900\sqrt[4]{G^9}$	$5,200\sqrt[4]{G^9}$
Shear along grain:		
Stress at ultimate, lb. per sq. in.	$2,650\sqrt[3]{G^4}$	$3,800\sqrt[3]{G^4}$

[1] See Table XXIII, column heading, for definition of modulus of rupture.

lumber. The idea of built-up lumber has been extended to the development of plywood-lumber built up of thin layers with the grain of successive layers usually at right angles, and all layers glued together with waterproof glue or impregnated and fastened together with plastic material under heat and pressure.

Plywood thus made has two advantages over ordinary lumber: (1) the tendency of any layer to shrink transversely to the grain under change of moisture content is resisted on account of the direction of the grain of the adjacent layers, and (2) the net shrinkage of the built-up wood is slightly greater than the shrinkage of ordinary lumber parallel to the grain.

Plywood is built up of an odd number of layers, and it has maximum strength if the face plies have their grain parallel to the maximum tensile or compressive stress. Plywood is built up of this odd number of plies so that shrinkage stresses will be symmetrical about the middle layer, and the tendency to warp the wood a minimum. For thin sheets three-ply and five-ply plywood is frequently used. The core of plywood may be veneer, lumber, or various combinations of the two, and the total thickness of sheet may be as small as $\frac{1}{16}$ in. or as large as 3 in. or sometimes even larger.

Table XXV gives values determined by Elmendorf for the tensile strength of plywood. The values used for the three-ply material are for plywood in which the same wood is used for surface and for middle plies. In the notes below the table, a method is indicated for computing the tensile strength of plywood in which surface plies and middle plies are made of different kinds of wood. The tensile strength of the ply with grain perpendicular to length of piece is then approximately two-thirds of the tensile strength of that of a solid board or sheet made of the same wood, with the same total thickness as the sheet or board, and with grain parallel to the tensile stress.

Under flexure plywood boards have about 85 per cent of the strength of a solid beam of the same wood and same size, if there are three or more plies and the face plies have their grain parallel to the tensile stress (figure given in the U. S. Forest Products "Wood Handbook").

Rigidity of Plywood Sheets and Resistance to Splitting. The rigidity of plywood sheets in a structure depends largely on the method of attachment. If nails are used for attaching a plywood sheet to a timber framework, the rigidity depends to a considerable extent on the lateral resistance of the nails. Tests of plywood panels glued to the studs of a framework have much higher rigidity than panels nailed to the studs.

Plywood permits fastening with nails or screws quite close to the edge of the sheet, because plywood offers more resistance to splitting than ordinary wood boards.

When a structure can be so designed that timber can be used as the material without danger of failure by longitudinal shear or by cross-grain tension, then, with the possible exception of some of the stronger alloys of steel and of light metals, timber will give the lightest structure. Plywood extends the possibilities of using the lightness of timber construction by lessening the danger of splitting or shearing along the grain of the wood.

It is evident that the strength of plywood will be dependent on the strength of the glue joint between layers of veneer. Table XXVI summarizes the properties and uses of various kinds of glue.

TABLE XXV. TENSILE STRENGTH OF PLYWOOD AND VENEER
Elmendorf, *Proc. A.S.T.M.*, Vol. 20, Part II, p. 340, 1920

Species	Number of tests	Moisture at test, per cent	Specific gravity [1] of plywood	Tensile strength [2] of three-ply wood parallel to grain of faces, lb. per sq. in.	Tensile strength [3] of single-ply veneer lb. per sq. in.
	a	*b*	*c*	*d*	*e*
Ash, black	120	9.1	0.49	6,180	9,270
Ash, commercial white	200	10.2	0.60	6,510	9,760
Basswood	200	9.2	0.42	6,880	10,320
Beech	120	8.6	0.67	13,000	19,500
Birch, yellow	200	8.5	0.67	13,210	19,820
Cedar, Spanish	115	13.3	0.41	5,200	7,800
Cherry (probably black cherry)	115	9.1	0.56	8,460	12,690
Chestnut	40	11.7	0.43	4,430	6,640
Cypress, bald	113	8.0	0.45	6,160	9,240
Douglas fir (coast type)	200	8.6	0.48	6,180	9,270
Elm, cork	65	9.4	0.62	8,440	12,660
Elm, white	160	8.9	0.52	5,860	8,790
Fir, true (probably white fir)	24	8.5	0.40	5,670	8,510
Gum (probably black gum)	35	10.6	0.54	6,960	10,440
Gum, cotton	80	10.3	0.50	6,260	9,390
Gum, red	182	8.7	0.54	7,850	11,780
Hackberry	80	10.2	0.54	6,920	10,380
Hemlock, western	119	9.7	0.47	6,800	10,200
Magnolia (probably evergreen)	80	8.8	0.58	9,220	13,830
Mahogany, African (probably Khaya species)	20	12.7	0.52	5,370	8,060
Mahogany, Philippine (probably tanguile)	25	10.7	0.53	10,670	16,000
Mahogany, true	35	11.4	0.48	6,390	9,580
Maple, soft (probably silver maple)	120	8.9	0.57	8,180	12,270
Maple, hard (sugar or black)	192	8.0	0.68	10,190	15,290
Oak, commercial red	115	9.3	0.59	5,480	8,220
Oak, commercial white	195	9.5	0.64	6,730	10,100
Pine, sugar	110	8.0	0.42	5,530	8,300
Pine, white	40	5.4	0.42	5,720	8,580
Poplar, yellow	155	9.4	0.50	7,390	11,080
Redwood	105	9.7	0.42	4,770	7,160
Spruce, Sitka	121	8.3	0.42	5,650	8,480
Sycamore	163	9.2	0.56	8,030	12,040
Walnut, black	110	9.1	0.59	8,250	12,380
Yucca species	33	7.3	0.49	2,210	3,320

Sample computation:

To obtain the tensile strength of three-ply wood consisting of two $\frac{1}{20}$-in. birch faces and a $\frac{1}{16}$-in. basswood core.

Parallel to face grain $= 2 \times \frac{1}{20} \times 19{,}820 = 1{,}982$ lb. per inch of width.

Perpendicular to face grain $= 1 \times \frac{1}{16} \times 10{,}320 = 645$ lb. per inch of width.

This computation neglects the tensile strength of the ply or plies perpendicular to the grain, which is comparatively small, and the results are therefore slightly in error.

[1] Specific gravity based on oven-dry weight and volume at test.

[2] Based on total cross-sectional area.

[3] Based on assumption that center ply carries no load. Values $1\frac{1}{2}$ times those in column *d*.

Data based on tests of three-ply panels with all plies in any one panel same thickness and species.

TABLE XXVI. PROPERTIES OF VARIOUS GLUES
Based on Technical Note 207, U. S. Forest Products Laboratory

Item	Animal glue	Casein glue	Vegetable glue	Blood glue	Liquid glue
Source of principal ingredient	Animal hides, bones, etc.	Casein from milk	Starch, generally cassava	Soluble dried blood	Animal glue, skins, bones of fish
Sq. ft. of surface covered per lb. of glue	25–35	35–55	35–55	30–100	No data
Mixing	Soaked in water, then melted	Mixed cold	Mixed with alkali and water with or without heat. Alkali not always used	Mixed cold	Applied as furnished by by manufacturer
Application	Applied warm with brush or mechanical roller	Applied cold with brush or spreader	Applied cold with spreader	Applied cold by hand or spreader	Applied cold or warm, usually by hand
Strength (in shear)	High grade; stronger than strongest American woods. Medium grades: slightly lower	About the same as medium grade animal glue	About the same as medium grade animal glue	Slightly less than medium grade animal glue	Good grade about the same as medium grade animal glue. Some grades very weak
Water resistance	Naturally low, can be increased by chemical treatment	High or low as required	Low	High	Low
Staining	Does not stain	Stains some species of wood	Stains some species of wood if caustic soda is used in making glue	Does not stain, but glue is very dark, and may show through veneer	Does not stain
Uses	High grade for strength; low grade sometimes used for veneer, especially where staining is undesirable	Mainly where water resistance is desirable in veneered or joint work	To some extent for joints, but mainly for veneer where good strength at low cost is prime factor	Almost entirely for water-resistant plywood and for parts to be molded after boiling in water	Mainly for repair work and gluing small parts by hand

Decay of Wood. The cells of wood with the water found in them furnish food for a variety of destructive bacteria and fungi. These bacteria and fungi feed on the moist wood fiber and cause rotting of the wood. Lack of moisture diminishes the food value of the wood, and hence seasoning, which removes moisture, diminishes the rapidity of decay of wood and lengthens its life. Well-seasoned timber which is not exposed to moisture retains its strength for many years. The usefulness of the seasoning process in preserving the life of timber structures which are exposed to moisture is limited by the fact that in such structures the wood soon reabsorbs moisture, and again furnishes abundant food for the destructive bacteria and fungi. In this connection it should be noted that timber kept continuously under water does not decay, though in sea water it may be attacked by marine boring animals, such as the teredo. In many locations termites have become a serious menace to wooden buildings and other timber structures.

Preservatives for Timber. The decay of timber exposed to moisture can be very greatly retarded if the fibers are impregnated with some substance which is poisonous to the decay-causing bacteria and fungi. An ideal preservative for timber would be poisonous to decay-causing organisms, would be capable of being injected into the innermost fibers of the pieces of timber treated, would be retained in the wood, and would be cheap. The two wood preservatives in common use are creosote and zinc chloride. Creosote is an oil, a product of coal-tar distillation. It is poisonous to wood-destroying bacteria, it is not soluble in water, and hence will not be dissolved out of timber by the action of rains or of flowing streams. It can be forced into the inner fibers of softwoods and of some hardwoods. Zinc chloride is violently poisonous to timber-destroying bacteria, can be readily forced into the inner fibers of wood, and is cheaper than creosote. It is, however, soluble in water, and is gradually dissolved out of timber which is exposed to water.

Preservative Processes for Timber. The simplest process of treating timber to preserve it against decay consists in simply soaking the pieces to be treated in an open tank of hot creosote or other preservative. This process does not impregnate the timber very thoroughly and it is wasteful of preservative. This "open-tank" process is used only for treating small lots of timber where the apparatus for more thorough treatment is not available.

The general method followed in the commercial treatment of timber either with zinc chloride or, as is more common, with creosote involves the following steps: (1) the seasoning of the timber; (2) the steaming of the timber in a large cylinder to soften the wood fiber; (3) the removal of air and moisture from the interior of the cylinder and from the wood fibers

by means of a vacuum pump; (4) the connection of the interior of the cylinder with a tank of preservative (creosote or zinc chloride)—the preservative rushes into the partial vacuum formed in the cylinder and penetrates some distance into the wood structure; (5) the application of pressure to the cylinder forcing the preservative into the innermost fibers of the timber; and (6) the removal of the pressure, after which the excess of preservative is allowed to drip off the timber and run into a tank.

Uses of Treated Timber. The treatment of railway ties to preserve them against decay is the most widely developed application of the timber-treating process. Usually the tie-treating process is carried on in a large plant, in which several cylinders about 150 ft. long by 10 ft. in diameter receive a number of small cars loaded with ties to be treated.

Timber for piles, especially for piles which are to stand in salt water, is also frequently treated with preservative. Poles for carrying electric wires, and fence posts are sometimes treated by the open-tank process over the ends which are to be placed in the ground.

The life of a softwood railway tie untreated with preservatives varies from 5 to 8 years; creosoted it will resist decay for 10 to 14 years. If railway ties are to be used in a very dry location, zinc chloride will be almost as effective as creosote in lengthening the life of the tie.

Strength of Treated Timber. The effect of the preservative process on the strength of timber has been the subject of much discussion, and several series of tests on the relative strength of treated timber and untreated timber have been made. Injury may be done to the timber if the preservative process is carelessly carried out; especially is there danger of injuring the timber by excessive pressure while it is being steamed. If the preservative process is carefully carried out, tests seem to indicate that the strength of the timber is but little impaired, if at all.

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Questions

1. What are the strong points and what are the weak points of wood as a structural material?

2. Why has wood been widely used for railroad ties?

3. What is the distinction between hardwood and softwood? Are hardwoods all stronger than the strongest softwoods? Name several species of hardwood and of softwood. What are the principal uses of softwoods? Of hardwoods?

4. Name some reasons why the ratio of consumption of wood to the growth of wood in the United States is somewhat smaller in 1950 than it was estimated to be 10 or 12 years ago.

5. From what region in the United States does the greatest supply of hardwoods come? From what region does the greatest supply of softwoods come?

6. What are the changes which take place in wood during seasoning? Why does proper seasoning improve the strength of wood?

7. What are annual rings of wood? What is heartwood? What is sapwood? Spring wood? Summer wood?

8. Why does shrinkage of wood during seasoning differ in different directions? What damage may result from too rapid seasoning?

9. In sawing boards from a log of wood, what is the difference between "plain-sawed boards" and "quarter-sawed" boards. What other names are used for these two terms and to what kinds of wood do the terms apply?

10. Compare the strong points and the weak points of "quarter-sawed" boards with "plain-sawed" boards.

11. How would you classify a piece of lumber that is 7 by 8 in. in cross section and 7 ft. long? A piece that is 3 in. in thickness, 8 in. wide, and 12 ft. long? One which is 2.5 by 6 in.? A piece of lumber 3.5 by 9 in.? One that is 5 by 10 in.?

12. Define rough lumber, surfaced lumber, and worked lumber. Distinguish between select lumber and common lumber.

13. Visit a lumber yard in your town or city and find out if the men there follow these classifications of grades and, if not, what classification and standards they do follow.

14. Discuss the effects of cross grain, knots, splits, "shakes," and wane on the strength and appearance of lumber. For a simple wooden beam carrying a vertical load, is a knot more injurious on the top surface or on the bottom? Why?

15. Compare the structure of Douglas fir with that of oak.

16. About how much will the strength and the stiffness of an air-seasoned hemlock be reduced if it absorbs water until its moisture content is 17 per cent?

17. If a torsion test were made on a round stick of wood, what kind of a failure would you expect?

18. Why is wood rather rarely used for tension members in structures?

19. Three columns are cut from a stick of lumber 6 by 6 in. in cross section. Their lengths are 4, 5, and 10 ft., respectively. The safe working stress for the lumber in compression is 960 lb. per sq. in. and the modulus of elasticity is 1,200,000 lb. per sq. in. What is the safe load which each column can carry?

20. How great would be the diameter of circular columns of the same lengths and timber to carry the same safe loads?

21. Three laminated columns such as are shown in Fig. 76(*B*) have over-all section 6 by 6 in. The laminated column is made up of planks of the same wood as the columns in questions 19 and 20. How much load could each of these three laminated columns carry safely?

22. What is the effect of long-continued steady load on wood structural members?

23. An oak stick under flexure will carry about one-third the load of a cast-iron bar of the same size. Under impact, the oak stick will withstand about three times the *energy* that the cast-iron bar will withstand without fracture. Explain.

24. Why does well-seasoned wood decay less than poorly seasoned wood?

25. How do chemical preservatives act to prevent decay?

26. What are some preservatives commonly used for wood? What are the advantages and drawbacks of each?

27. Outline briefly two processes for treating wood with preservatives. What is the effect of the preservative process on the strength of wood?

28. How much may the life of a wooden railway tie be lengthened by the use of preservative?

29. Why are white oak ties not creosoted?

30. What is plywood? What advantages does it have as a structural material over ordinary timber?

31. Why is plywood made up with an odd number of plies?

32. For what general classes of structures is wood suitable? Give examples. For what classes of structures is it unsuitable? Give examples.

CHAPTER XIII

BUILDING STONE AND CERAMIC MATERIALS

General Uses of Building Stone. Since the earliest known times stone has been used as a material of construction for walls, foundations, and dams. Stone arches have been in use for many centuries. Today the use of stone masonry for purely structural purposes is of diminishing importance owing to the great development of reinforced concrete, but building stone is still used for buildings and structures in which appearance and permanence are large factors in design. Of the stone quarried in the United States not over 50 per cent is used for structural purposes, the remainder being used for crushed stone for roads, railroad ballast, and concrete.

Varieties of Building Stone. The common building stones include granite, limestone (including marble), sandstone, and slate; there are many varieties of each of these general classes. The granites are the hardest and strongest building stones in general use, the sandstones are next in hardness and strength, and the limestones are, in general, the softest and weakest (though the stronger limestones are stronger than the weaker sandstones). The use of slate is, in general, confined to roofing and some interior work in buildings. The harder and stronger a building stone is, the more difficult and expensive it is to quarry blocks of that stone and to dress them to shape. In general, the harder stones are the more durable. The life of American stone structures before disintegration under weathering (the action of frost, chemical action from gases, etc.) is estimated to vary from about 12 years for soft sandstone to several centuries for the harder granites.

Stone Quarrying and Stone Cutting. Blocks of building stone are cut or blasted from the ledges of rock which constitute a stone quarry. These rough blocks are dressed to shape in stone sheds, usually located near the quarries. The squaring and final shaping of the stone are done by cutting tools operated either by hand or, more commonly, by compressed air. Power-driven planers, lathes, and saws for shaping large pieces of stone are used to a considerable extent, especially for shaping marble.

Masonry Construction. In laying together individual pieces of stone to form masonry, various methods are followed. The simplest form of masonry is *riprap*, which consists of uncut stones piled together without

any adhesive mortar between them. Riprap is used for protective embankments for streams, and for low stone walls. It has very little structural strength, and is not used for structures subjected to any great amount of load. *Rubble* masonry is made up of uncut stones piled and cemented together with a matrix of mortar. In *uncoursed* rubble the stones are piled without any attempt at regularity of arrangement; in *coursed* rubble the stones are piled in layers as regularly arranged as possible. *Squared* stone masonry is built up of blocks of stone dressed to regular shapes. *Cut*-stone masonry or *ashlar*[1] masonry is built up of blocks of stone squared and with the faces dressed to a fairly smooth surface.

Strength of Stone and of Stone Masonry. Stone masonry is used in structures principally to resist compressive stress. Individual blocks of stone are sometimes used to resist bending, such as the lintels for windows and doors, or as top slabs for culverts. The strength per square inch of specimens of stone is very much greater than the strength per square inch of masonry built from that kind of stone, on account of the presence in masonry of mortar joints, which are weaker than the stone. Strong stone, in general, makes stronger masonry than does weak stone, and on this account, as well as on account of the occasional use of individual stone slabs in flexure, the strength of different kinds of stone is of importance to the structural engineer. The actual strength of stone masonry depends largely on the strength of the mortar used and on the closeness of fit between adjacent stones. Ashlar masonry is about seven times as strong as uncoursed rubble masonry. The compressive strength, the flexural strength, and the strength in shear or common American building stones are given in Table XXVII. Allowable working stresses for different types of stone masonry are given in Table XI, Chap. VII.

Ceramic Materials. Ceramic materials for engineering application include such fired-clay products as brick, tile, terra cotta, porcelains, drain pipe and sewer pipe. Clays suitable for the manufacture of building brick are widely distributed. Clays which can be used for paving brick are less widely distributed. The refractory clays used in making terra cotta are about as widely distributed as the clays used for paving brick. The refractory clays used in making firebrick and the white burning clays used for porcelain and whiteware products are found in only a few places. Ceramic materials utilize a clay base containing silicates and other substances. The clay is formed in final shape and then heat-treated to secure desired properties.

Brickmaking Processes. Three brickmaking processes are in common use: the soft-mud process, the stiff-mud process, and the dry-press

[1] By some authorities the term *ashlar* is used only for cut-stone masonry in which the joints are not more than ½ in. thick.

process. These processes differ in the moisture content and consistency of the clay used and in the method of forming the bricks.

Soft-mud bricks are formed by forcing the soft clay into wooden or metal molds which are wet or sanded to prevent the sticking of the clay. The bricks are dumped from the molds on to metal or wooden pallets for drying. Hand molding has been almost entirely replaced by machine operation.

Stiff-mud brick is formed by continuous extrusion of the plastic clay by means of an auger in a machine resembling a meat grinder, through an orifice or a die which delivers a ribbon of clay with two

TABLE XXVII. VALUES FOR STRENGTH AND STIFFNESS OF AMERICAN BUILDING STONE

Values based mainly on test data from the Watertown (Mass.) Arsenal

Stone	Ultimate in compression, lb. per sq. in.		Modulus of rupture (computed ultimate in cross-bending), lb. per sq. in.		Shearing strength, lb. per sq. in.[1]	Modulus of elasticity (flexure), lb. per sq. in.	Weight (av.), lb. per cu. ft.
	Range	Av.	Range	Av.	Av.	Av.	
Granite...	15,000–26,000	20,200	1,200–2,200	1,600	2,300	7,500,000	165
Marble...	10,300–16,100	12,600	850–2,300	1,500	1,300	8,200,000	170
Limestone	3,200–20,000	9,000	250–2,700	1,200	1,400	8,400,000	160
Sandstone	6,700–19,000	12,500	500–2,200	1,500	1,700	3,300,000	135
Slate.....		15,000		8,500		14,000,000	175

[1] It is doubtful whether tests in direct shear give true shearing strength; probably the values are more closely associated with tensile strength.

dimensions of the brick, usually the width and length. This is cut into sections, giving the third dimension. The cutting machine cuts the plastic clay with a wire. After the bricks are cut from the ribbon of clay, they are stacked on cars and carried in a long heated tunnel for drying.

For making dry-pressed brick, the clay is moistened only slightly. It remains granular in consistency. The bricks are formed under very high pressure. The clay is charged into a metal mold box and is compressed by plungers acting from the top and the bottom of the box. The mold used makes one brick at a time. The bricks are usually stacked on kiln cars and are carried through a drying tunnel and into a continuous kiln for the firing operation.

Hollow wares, such as drain tile and building blocks, are formed by a process resembling the process for stiff-mud bricks. Sewer pipe has to be formed by a special pressing process on account of the bell or socket on the pipe.

It takes from a few hours to several days to dry the bricks, depending on the characteristics of the clay and of the dryer used.

Temperatures ranging from 1800°F. for ordinary red brick up to 2700°F. for fire brick are required for firing. Intermittent or periodic kilns have generally been used, but continuous kilns of the car-tunnel type are coming into extensive use.

The A.S.T.M. specifications for clay or shale-building brick cover three grades: (1) *grade SW*, bricks which are likely to be exposed to freezing temperatures while saturated with water; (2) *grade MW*, bricks which are *not* likely to be exposed to freezing temperatures while saturated with water; and (3) *grade NW*, bricks for interior masonry, or for outside masonry where there is no frost action, or where the rainfall is less than 20 in. per year.

Table XXVIII shows the strength requirements and the allowable water absorption and allowable saturation coefficient for these three grades of building brick.

TABLE XXVIII. A.S.T.M. PHYSICAL REQUIREMENTS FOR CLAY OR SHALE BUILDING BRICK

Designation	Minimum compressive strength (brick flatwise), lb. per sq. in. (gross area)		Maximum water absorption by 5-hr. boiling, per cent		Maximum saturation coefficient[1]	
	Av. of 5 bricks	Individual	Av. of 5 bricks	Individual	Av. of 5 bricks	Individual
Grade *SW*	3,000	2,500	17.1	20.0	0.78	0.80
Grade *MW*	2,500	2,200	22.0	25.0	0.88	0.90
Grade *NW*	1,500	1,250	No limit	No limit	No limit	No limit

[1] The saturation coefficient is the ratio of absorption by 24-hr. submersion in cold water to the absorption after 5-hr. submersion in boiling water.

A comparison of the values for compression tests of single bricks with the allowable working stress for brick walls and columns in Table XI seems to indicate a very high factor of safety, even for grade *NW* bricks. As a matter of fact, the compressive strength of individual bricks is not as important a factor in the strength of a brick wall or column as is the strength of the mortar used and the weakening of the brick by being frozen while saturated with water. The value of the compressive strength required in single-brick tests merely gives a relative evaluation of the strength of the bricks.

Paving Brick, Firebrick, and Sewer Pipe. Paving blocks are usually made from shale (clay, hardened to a rocklike structure) and in the proc-

ess of manufacture a higher temperature of firing is used than in making building bricks. The temperature for paving brick is so high that the burned clay has a slightly vitreous (glassy) surface.

Firebrick capable of resisting high temperatures may be divided into acid, basic, and neutral firebrick. *Acid* firebricks, used for such purposes as the lining of acid-steel furnaces, are made from selected fireclay or from a mixture of a silica-bearing material (sand or ganister) and lime.

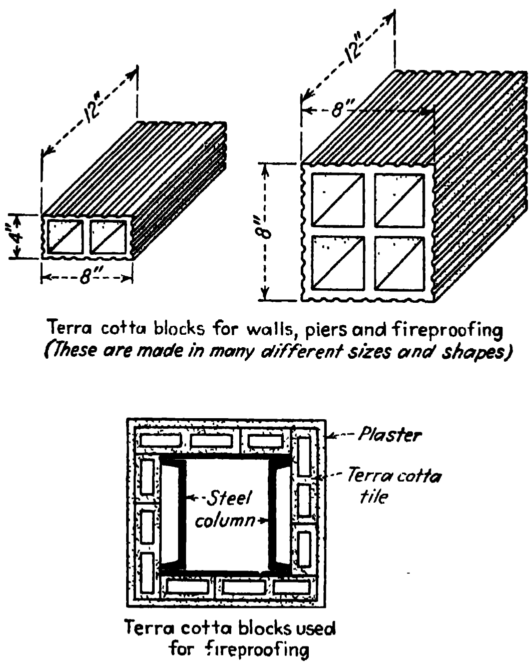

FIG. 79. Typical forms and uses of terra-cotta blocks.

Acid firebricks are burned at a very high temperature. *Basic* firebricks, used for the lining of basic-steel furnaces, are made from clay mixed with some substance containing magnesium or aluminum (magnesia or bauxite). Basic firebricks are also burned at a very high temperature. Neutral firebricks are made of a mixture of chrome iron and fireclay.

Sewer pipe is not porous and is used for locations where it is not desired to have the pipe absorb water from the surrounding soil. The joints between different pieces in a line of sewer pipe are usually made tight by the use of portland-cement concrete mortar.

Terra Cotta. Terra cotta is made in the same general way as is brick. The raw material is carefully selected clay. Hard terra-cotta building blocks, fireproofing material, and the tile are made by burning

the clay at such a high temperature that the resulting product has a slightly vitrified surface. Hard terra cotta is a strong, brittle material. Porous terra cotta, sometimes called terra-cotta lumber, is made by burning a mixture of clay and straw or sawdust. The combustible straw or sawdust burns out, leaving the material light, porous, and tough. Nails and screws may be driven into porous terra cotta and a wood saw can be used to cut it. Figure 79 shows typical forms of terra-cotta units used for building blocks and for fireproofing.

Strength of Porcelain and Stoneware. The strength of porcelain and stoneware, both special fired-clay products, is of importance, especially in connection with the design and use of strain insulators—insulators for electric transmission lines, which have to carry the load brought on them by the weight of spans of wire. The results of a series of tests by Prof. J. E. Boyd at The Ohio State University (see reference 4 at the end of this chapter) indicate that for porcelain the tensile strength is not less than 3,000 lb. per sq. in. and for stoneware from 1,100 to 2,200 lb. per sq. in.; the ultimate compressive strength for porcelain and for high-grade stoneware is about 20,000 lb. per sq. in. The modulus of elasticity for both tension and compression is about 10,000,000 lb. per sq. in. for porcelain, and about 7,500,000 lb. per sq. in. for stoneware.

Sand-lime Brick. Sand-lime bricks are not burnt-clay products, but as they are made of the same standard size as are clay building brick, and as their uses are the same as those of building brick, they will be mentioned here. Sand-lime bricks are made of a finely ground mixture of slaked lime and sand. The materials, thoroughly mixed, are pressed into shape in molds, after which they have sufficient stiffness to hold their form under their own weight. The molded bricks are carried on small cars into a long cylinder where they are subjected to steam at a pressure of about 120 lb. per sq. in. for a period of about 10 hr. The steam causes cementing action between the lime and the sand, and when the sand-lime bricks are taken from the steam cylinder they have a fairly high strength. The strength of sand-lime bricks increases for some months after they are made. Sand-lime bricks are used for general building purposes. The strength of sand-lime brick is about three-quarters that of ordinary clay building brick (A.S.T.M. grade *NW*).

Strength of Brick and Terra Cotta and of Brick Masonry and Terra-cotta Masonry. As in the case of stone masonry, plain brick masonry is always used in compression. The compressive strength per square inch of brick masonry is much less than the compressive strength of the individual bricks. In general, strong bricks make stronger masonry than do weak bricks, but the quality of mortar used, the closeness of fit between adjacent bricks, and the care used in laying the bricks, all are

important factors in the strength of brick masonry. In walls, foundations, and pavements cracks occur most commonly along the mortar joints. When individual bricks break they nearly always crack across, due to the inclined tensile stress accompanying shear, rather than crush under the compressive stress, and the strength under punching

TABLE XXIX. STRENGTH IN COMPRESSION OF BRICK AND OF TERRA-COTTA BLOCK PIERS AND WALLS

The values given are based on test data from Watertown Arsenal, Cornell University, U. S. Bureau of Standards, and the University of Illinois. The weight of masonry may be taken as about 5 lb. per cu. ft. less than the weight of the stone or brick used

Brick or block used	Mortar	Ultimate in compression, lb. per sq. in.
	Piers	
Vitrified brick	1 part Portland cement, 3 parts sand	2,800
Pressed (face) brick	1 part Portland cement, 3 parts sand	2,000
Pressed (face) brick	1 part lime, 3 parts sand	1,400
Common brick	1 part Portland cement, 3 parts sand	1,000
Common brick	1 part lime, 3 parts sand	700
Terra-cotta block	1 part Portland cement, 3 parts sand	3,000
	Walls	
Common brick	1 part Portland cement, 1¼ parts lime, 6 parts sand	950
Common brick	1 part Portland cement, 3 parts sand	1,150
Hollow tile joints staggered	1 part Portland cement, ¼ part lime, 3 parts sand	1,270

Test data for piers built of sand-lime brick are lacking but, judging from test data for individual brick, sand-lime brick piers might be expected to be about three-quarters as strong as piers built of common brick.

shear, or possibly under flexure, is a better general index of the quality of individual brick than is the compressive strength.

Tests of compressive strength of brick masonry have been made at various testing laboratories. Table XXIX gives the summarized results of a number of such tests. Table XI, Chap. VII, gives allowable working loads on brick and terra-cotta masonry.

A recent development which increases the field of usefulness of brick

as a structural material is *reinforced brickwork.* The principle of reinforced brickwork is the same as that which has been so successful in reinforced concrete. Steel rods are imbedded in the tension side of brickwork beams, thus utilizing the compressive strength of the brickwork and the tensile strength of steel.

Durability of Brick and of Terra-cotta Masonry. Brick masonry and terra-cotta masonry if well made from good materials are as nearly permanent as any structural material. However, they may finally suffer disintegration under weathering, and usually the freezing and consequent expansion of absorbed water is a prominent factor in the disintegrating process. Porous brick absorbs much more water than does hard-burned brick, and porous brick, in general, weathers poorly. Lime and other salts are dissolved out of brick masonry which is exposed to the weather and sometimes streaks of lime are deposited on the surface of the masonry as the result of this leaching-out action. Sand-lime brick when new is nearly white and, like other light-colored brick, is particularly liable to show disfigurement by the leaching out of salts.

The mortar joints in either stone or brick masonry are especially liable to damage by weathering. Pointing masonry consists in filling the edges of the joints to the depth of about an inch with rich mortar packed in as compactly as possible. This pointing offers resistance to the action of the weather at the joints, and increases the endurance of the masonry.

Ceramics for Strength at High Temperatures. One of the major difficulties in the use of metallic materials, particularly steels, is their lack of high-temperature strength. This has limited progress in heat engines, particularly gas turbines, steam turbines, and rockets. In these fields the thermodynamic cycle efficiency would be materially increased if temperatures of 2000 to 3000°F. could be used continuously. Some metal alloys, such as chromium-nickel-iron, nickel-molybdenum, and chromium-nickel-cobalt, have been used at temperatures as high as 1200°F. but are unsatisfactory at higher temperatures. Ceramic materials, such as refractory compounds which contain combinations of oxides of beryllium, aluminum, zirconium, thorium, magnesium, and calcium, have been found to be promising materials for resistance to very high temperatures. These oxides are generally found in natural ores, and it is possible that still other ores may be found which will be as good as, or better than, any of the above.

One very difficult phase of the problem of developing high-temperature ceramics is that all ceramic materials tried so far are very brittle and have very little strain energy to resist fracture. Not only are there stresses set up by external load, but thermal shock due to internal

stresses caused by heating, cooling, or change of the crystalline structure must also be withstood.

These brittle ceramics are very sensitive to stress concentration at "stress raisers," and so the method of attaching turbine blades to the disk of a turbine is a difficult problem in design. Turbine blades must withstand both cycles of long-continued stress and thermal shock and present a problem even more difficult than that of ceramics for stator (guide) blades for turbines and combustion chambers. Ceramic coatings for turbine blades have been tried and seem to be of some value. They can be used on metal blades already available. The principal value of such coatings is to protect the surface of the metal against corrosive attack and a secondary value is that they provide some insulation against high temperature. However, the insulating effect against high temperature will be small, since the ceramic coatings must be very thin to adhere strongly to the metal and to withstand the deformation of the metal blade without cracking.

The properties which make ceramic materials useful in engineering applications may be summarized as follows: (1) chemical stability, including resistance to corrosion and to weathering; (2) electrical insulation; (3) resistance to deterioration at high temperature; (4) low-density interior, resulting in light weight, combined with high-density glazed surface.

These advantages are limited in application by the disadvantages of ceramic materials which include (1) very low elastic strength; (2) lack of toughness, which means brittleness and low thermal-shock resistance, and (3) inability to machine or form the material after it has been fired.

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Questions

1. Name the general classes of building stone.

2. Name one or more structures or structural parts which are built of the following building stones; granite, sandstone, limestone, slate, marble. Why do you think the particular stone was chosen in each case?

3. Name structures or structural parts which might be built of rubble masonry. Of squared-stone masonry. Of cut-stone masonry. Give reason for using the particular type of masonry in each case.

4. Do you agree with the footnote to Table XXVII? Give your reasons. Do you agree with the footnote to Table XXIX? Give your reasons.

5. Describe the general process of making brick or other fired-clay structural material.

6. What is firebrick? Soft-mud brick? Stiff-mud brick? Dry-pressed brick? How do paving bricks differ from building bricks?

7. What is terra cotta? How made? For what used?

8. What is sand-lime brick? Is it a fired-clay product? Would you advise its use for warehouse columns? For the walls of a church? Give your reasons.

9. Estimate the load which would cause failure in compression of a short brick column 12 by 12 in. in cross section and made of A.S.T.M. grade *SW* brick with mortar joints. What load if portland cement mortar were used? How large a piece of Douglas fir would be required to carry the same *safe* load as the *safe* load for the brick column (see Table XI, Chap. VII)?

10. What causes tend to shorten the life of brick masonry? Of stone masonry? Of timber structural parts? Of a steel structure?

11. In what general classes of structures and machines are brick and tile used?

12. How is terra cotta used as a fireproofing material?

13. Why are ceramic materials being studied for use in parts of machinery subjected to very high temperature?

14. What class of ceramic material seems best suited to withstand heavy load at very high temperature? What are the strong points and the weak points of these ceramic materials?

15. In what ways does a coating of ceramic material strengthen the steel blade of a gas or steam turbine under high temperature? Why must a coating of ceramic material on a turbine blade be thin?

16. Search through technical magazines or other publications to see if you can find any improvement in turbine blades since the writing of this book (1952).

CHAPTER XIV

CEMENTING MATERIALS: GYPSUM, LIME, PORTLAND CEMENT, AND OTHER HYDRAULIC CEMENTS

Cementing Materials. When mixed to a paste with water a number of substances possess the property of hardening into a solid under the chemical and crystallizing actions set up in the paste. Such substances are very valuable to the structural engineer. Walls, foundations, piers, and other structural units may be constructed by filling molds with the paste and allowing it to harden into a solid of the desired shape, or the paste may be used as a binding material for brick, concrete, or stone masonry. The principal cementing materials used in structural work are gypsum, lime (including quicklime, hydrated lime, and hydraulic lime), natural cement, and portland cement.

Gypsum. Gypsum is a combination of sulfate of lime with water of crystallization ($CaSO_4 + 2H_2O$). Large deposits of impure gypsum rock are found in various localities in the United States. If gypsum rock is subjected to a temperature exceeding 212°F., a portion of the water of crystallization is driven off and the solid residue left, when finely ground, is capable of reabsorbing water and hardening into a solid mass. The nature of the product depends on the purity of the raw materials, upon the temperature used in driving off the water of crystallization, and upon the addition of foreign ingredients to retard or accelerate the set. The products of the calcination of gypsum rock are marketed under a variety of names, such as plaster of paris, dental plaster, hard-wall plaster, Keene's cement, and gypsum plaster.

Manufacture of Gypsum Products. The general process of preparing gypsum products as used in the United States consists in (1) grinding gypsum rock, which is the raw material most commonly used; (2) calcining a charge of ground gypsum rock at a temperature varying from 270 to 400°F.; (3) fine grinding of the calcined product; (4) for some gypsum products the addition of substances which retard the setting of the calcined powder when mixed with water. Gypsum plaster to be used for wall finish is rendered more plastic by the addition of clay or of hydrated lime. The cohesiveness of such plaster is increased by adding hair or shredded wood fiber.

Structural Uses of Gypsum Products. As a structural material gypsum plaster is very light, is a good fire resistant, is inexpensive, and

possesses a fair degree of compressive strength. Its general use is for structural members in which lightness or fire-resisting qualities are of prime importance. Gypsum plasters are widely used for wall finish. Gypsum blocks are used for building curtain walls in buildings (curtain walls are those carrying no load from floors above them), for roof slabs, and for fireproofing around columns. Typical forms of gypsum blocks and tile are shown in Fig. 80. Structural gypsum weighs not more than 80 lb. per cu. ft. The lightness of gypsum makes it possible for workmen

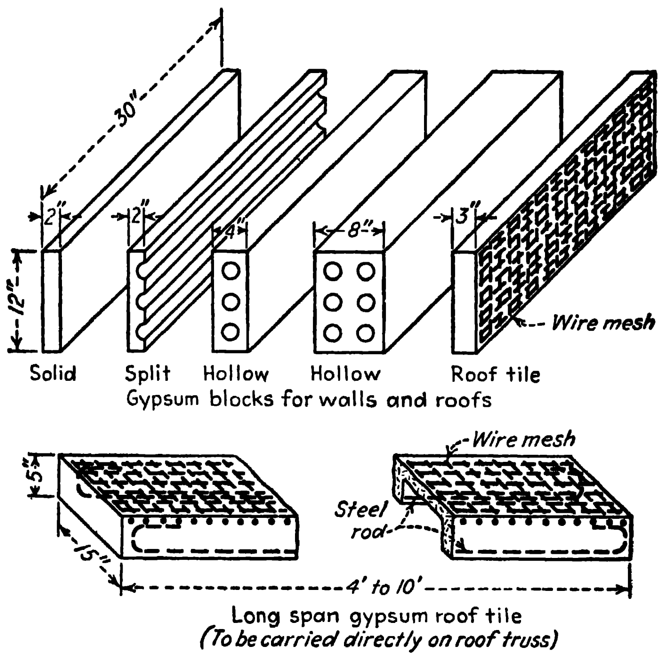

FIG. 80. Typical forms of gypsum blocks and tile.

to handle large-sized blocks, which makes the work of wall-building or of roof-laying quicker. For roof slabs and floor slabs a mixture of gypsum and wood fiber reinforced with steel wire is used. Gypsum mortar is used for the binding of gypsum fireproofing and for hard-wall finish. Gypsum is also used for dental molds, pottery molds, and industrial molds and models.

Gypsum as a Fireproofing Material. Gypsum makes a good fireproofing material for steel structures. The strength of gypsum is destroyed by long-continued heat when the water of crystallization is finally driven off, but a great deal of heat is required to evaporate the water of crystallization, and as the evaporation proceeds the gypsum

does not crack or spall, but its surface is converted into an anhydrous powder which acts as an excellent heat insulator, retarding the further evaporation of water of crystallization of the inside layers of gypsum. Gypsum blocks are used for fireproofing in much the same manner as is shown in Fig. 79 for terra-cotta blocks.

Strength of Structural Gypsum. The ultimate compressive strength of test cylinders of gypsum has been found to vary all the way from 70 up to 3,000 lb. per sq. in., depending upon the amount of water used in mixing the gypsum paste, the completeness of drying out of water after the gypsum paste has set, the amount of foreign ingredients mixed with the gypsum to retard its rate of setting, and the temperature used in calcining the gypsum rock. For highest strength the least possible amount of water should be used in mixing the gypsum paste. From 33 to 38 per cent of water is necessary to make gypsum paste sufficiently plastic to fill molds properly, and this percentage of water is more than sufficient to hydrate the gypsum. For gypsum from the same source of raw material, uniformity of consistency of gypsum paste ensures a good degree of uniformity of strength.

With care in mixing and drying out, gypsum can be produced regularly with a compressive strength of 1,400 lb. per sq. in. However, when practicable, tests should be made to determine the strength of any lot of gypsum blocks or other structural members.

Gypsum gains its full strength in a few hours if carefully kiln-dried, and air-cured gypsum gains strength so rapidly that forms may be removed the day after the gypsum is poured. Gypsum is weakened by prolonged exposure to water and should not be used where it will be kept wet for considerable periods of time.

The modulus of elasticity for structural gypsum is about 1,000,000 lb. per sq. in. The stress-strain diagram for gypsum cured under certain conditions is very nearly a straight line up to the ultimate.[1]

Gypsum-cement Compounds. There are on the market a number of gypsum-cement compounds made under new methods of manufacture, which have developed in laboratory tests strength properties much higher than the values obtained previously for gypsum. The trade name "Hydrocal" has been given to this group of special gypsum-cement compounds. Test values are reported as follows:

Mixing water: 40 parts to 100 parts of compound for pouring
25 parts to 100 parts of compound for molding
Tensile strength: 600–1,000 lb. per sq. in.

[1] This property has made possible the development of the "plaster model" method of studying stress distribution in complex shapes (SEELY and JAMES, *Univ. Ill. Eng. Expt. Sta. Bull.* 195; also SEELY and DOLAN, *Bull.* 276).

Compressive strength: 5,000–9,000 lb. per sq. in.
10,000–13,000 lb. per sq. in.—molded under pressure
Modulus of rupture (computed flexural strength): 900–2,400 lb. per sq. in.
Modulus of elasticity: 1,200,000–1,800,000 lb. per sq. in.
Weight (dry) per cubic foot: 82–112 lb.

This product has been used for the same type of structural members as gypsum and the test values give promise of use as a substitute for other cementing materials in locations where the gypsum-cement compound would not be exposed to the weather or to water.

Lime. The basis of the cementing action of lime mortar is the carbonation of the calcium hydroxide formed by the reaction of water with calcium oxide. Calcium oxide (CaO) is known as *quicklime.* It is prepared by heating limestone, which is mainly calcium carbonate ($CaCO_3$). Under the influence of heat, carbon dioxide is driven off, leaving calcium oxide or quicklime.

The heating or burning of limestone to produce lime is carried on in a brick-lined vertical shaft known as a limekiln, or in a rotary kiln like that used for burning portland cement clinker.

In the vertical kiln the fuel may be either bituminous coal, natural gas, producer gas, or oil. If bituminous coal is used as fuel, it is burned on grates at the side of the shaft. When gas or oil is used as fuel, it is fed into burners located at the bottom of the kiln. The limestone is fed into the top, the hot gases pass through the limestone, and the quicklime produced is removed at the bottom. In another type of vertical kiln, alternate layers of limestone and coke are fed into the top of the shaft.

In the rotary kiln, powdered coal, oil, or gas is used as fuel. This kiln consists of a long cylindrical steel shell lined with special fire brick and inclined slightly from the horizontal. The limestone is fed into one end of the kiln and the quicklime produced comes out the other. Quicklime must not be left exposed to the air. If it is so exposed, it absorbs carbon dioxide and is then transformed more or less completely to powdered calcium carbonate (air-slaked lime) and is useless for cementing purposes.

Hydrated Lime. If quicklime is mixed with about one-third its weight of water, it is changed from calcium oxide to calcium hydroxide [$Ca(OH)_2$]. This change is accompanied by the evolution of considerable heat and by a very great increase in volume. The product is a fine white powder which, when mixed with more water, absorbs water of crystallization and hardens. If it is attempted to use lime as a mortar unmixed with other substances, the great shrinkage which takes place while the hardening process goes on causes wide cracks in the hardened mass. A mixture of 1 part hydrated lime and 2 parts sand is commonly used to make lime mortar.

Two methods of making lime mortar are in use; in one, quicklime is

brought to the place where mortar is to be used, and is mixed with water, or "slaked" on the job by the workman; in the other method, the quicklime is slaked at the kiln under expert supervision, and the amount of water necessary for complete slaking, carefully computed, is added. The slaked lime is ground fine, screened through a fine sieve, and packed in bags. On the job this hydrated lime is mixed with sand and water to form mortar.

Lime mortar will not harden under water nor in any place unless air has free access to it. Its principal uses are for the binding material for brick, concrete, and stone masonry, and for plastering interior walls.

Natural Cement and Other Miscellaneous Hydraulic Cements. There are large deposits of clay-bearing limestone in the United States. This material, when heated to about 2000°F., gives off carbon dioxide, leaving a clinker. This clinker, when ground fine, is "natural" cement. It will not slake in air and, when mixed with water, hardens either in air or under water.

In some countries there are deposits of volcanic ash from which a hydraulic cement (one which will set under water) is made by grinding up clayey material from this ash and mixing it with hydrated lime. This is known as pozzuolana cement and is of historic interest from its wide use by the engineers of the Roman empire.

Portland-pozzuolana cement is made by intergrinding with portland cement clinker a pozzuolanic material such as volcanic ash, calcined clay, or other siliceous materials that possess pozzuolanic properties; that is, they have the ability to combine with lime in the presence of water to form stable compounds having cementatory properties.

Slag cement made from a mixture of hydrated lime and blast-furnace slag was formerly quite commonly used. This slag cement should be carefully distinguished from portland cement made with blast-furnace slag as one of its ingredients, and from "portland-blast-furnace slag" cement which is made by intergrinding iron blast-furnace slag with portland cement clinker.

Portland Cement. To the engineer the most important of the cementing materials is portland cement. It comprises about 97 per cent of the total production of the various hydraulic cements manufactured in the United States. Portland cement is made from an artificial mixture of lime-bearing materials with clayey material. The mixture is burned to a clinker at a temperature of incipient fusion and afterward ground to a fine powder. Portland cement does not deteriorate to any appreciable extent in dry air. When mixed with water, it hardens in air or under water and in hardening portland-cement mortar shrinks much less than do other kinds of mortar.

Raw Materials for Portland Cement. The lime-bearing material used

for portland-cement manufacture is some form of calcium carbonate ($CaCO_3$); limestone, marl, chalk, or oyster shells are the materials commonly used. The clayey materials include clay, shale, and blast-furnace slag (which also contains some calcium carbonate). In the Lehigh Valley region, portland cement is produced from cement rock, which is a natural mixture of limestone and shale in nearly the right proportions for making portland cement. In other regions, deposits are found consisting of alternate layers of limestone and shale, or else of limestone and clay near to each other. In some locations oyster shells, or beds of marl or of chalk, furnish the lime-bearing ingredient. Near the great pig-iron centers, blast-furnace slag furnishes the clayey ingredient and some of the lime and a very pure limestone is used to furnish the remainder of the lime-bearing ingredient. In some plants sand or sandstone, or iron materials, are used in addition to the limestone and clayey materials.

In the manufacture of portland cement, two processes are employed, called the "dry" and "wet" process. Figure 81 shows a diagram of these two processes. The lime-bearing and clayey ingredients are first crushed to pebble size (unless the raw material is found in a finely divided form). In the dry process the raw materials, after crushing, are dried in horizontal rotary driers and mixed in the proper proportion, which is determined by chemical analysis. The raw materials are then reduced to a fine powder in rotating steel cylinders containing steel balls which are known as "ball" or "tube" mills; vertical grinding mills are also sometimes used. The fine powder is then carried to blending silos and from the blending silos to the ground-raw-material storage silos. Material from these silos is carried to a hopper or kiln feeder from which it is fed to rotary kilns. These kilns range in diameter from 8 to 15 ft. and in length from 100 to 520 ft. They are lined with special firebrick. The kilns make from 60 to 80 revolutions per hour and are heated by gas, oil, or by burning a blast of powdered coal. They are slightly inclined from the horizontal; the material fed into them gradually travels from one end to the other and is heated to partial fusion at a temperature of about 2800°F. Near the discharge end the clay and lime combine chemically to form a hard clinker about the size of marbles. This clinker is cooled in clinker coolers and then carried to storage bins. The final step in the production of portland cement is to grind the clinker from the storage bins to a very fine powder in ball and tube mills with a carefully measured amount of gypsum, which is added to regulate the setting of the finished product. In case air-entraining portland cement is being produced, a small amount of a suitable air-entraining agent also is added at this stage of the process.

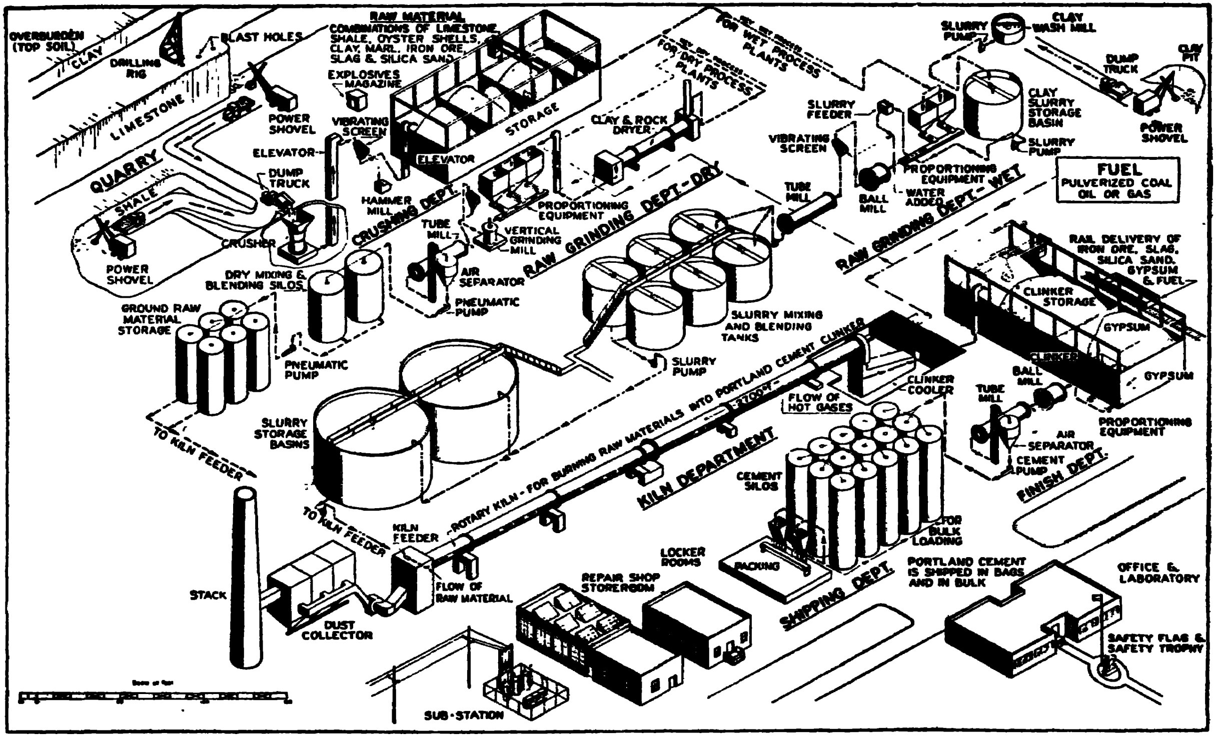

FIG. 81. Isometric flow chart of manufacture of portland cement. (*Courtesy of the Portland Cement Association, Chicago, Ill.*)

In the wet process the mixture of raw materials is ground with from 30 to 50 per cent of water. The slurry thus formed, after careful mixing and blending, is pumped from slurry storage basins to the kiln feeder and fed into the kiln. Drying of the wet mixture takes place during the first part of the progress through the kiln.

Portland cement is shipped in bulk or in paper bags, each containing 1 cu. ft. of cement which weighs 94 lb. Four bags of cement (376 lb.) are equivalent to one barrel. Cement shipped in bulk is batched by weight when used on the job.

High-early-strength Portland Cement, Calcium-aluminate Cement. High-early-strength portland cement was developed to meet the demand for concrete which gains strength quickly, so that forms may be removed soon after placing, or so that a highway slab may be opened to traffic at the earliest possible moment. High-early-strength cement (type 3) is made of the same raw materials as normal portland cement (type 1). The lime content of such cement is somewhat higher than that of normal portland and it is ground finer. High-early-strength portland cement develops as high strength in concrete in 3 or 4 days as normal portland cement concrete develops in 14 days. High-early-strength cement costs somewhat more than normal portland cement.

Calcium-aluminate cement is made by fusing a suitably proportioned mixture of aluminous and calcareous materials and grinding the resulting product to a fine powder. The raw materials are bauxite and limestone. In the United States calcium-aluminate cement is produced in a rotary kiln of a type similar to that used in the manufacture of portland cement. The fused cement clinker after cooling is ground to a fine powder. The setting is controlled by the rate of cooling of the fused product and by the addition of suitable retarders.

Calcium-aluminate cement hardens rapidly and develops a very high strength in 24 hours. In the United States calcium-aluminate cement is used largely for special applications, such as refractory concrete for furnace linings, and for concrete where high resistance to weak sulfate solutions, industrial wastes, and organic acids is desired.

Types of Portland Cement. Specifications of the A.S.T.M. and the U. S. Government contain requirements for five types of portland cement, two of which may be regarded as special cements. The five types are:

Type 1: This is the most common type of cement. It is a general-purpose cement suitable for all uses except where special conditions warrant the selection of another type.

Type 2: This type of cement develops somewhat less heat during hardening and has somewhat higher sulfate-resisting properties than type 1 cement. Its particular field is in rather large structures in which a somewhat lower heat during

hardening is desired than that developed by type 1. It is specially suited for large piers or other concrete structures when such structures are to be placed during hot weather. In cold weather, heat developed during hardening may be of actual advantage, and type 1 cement may be preferable. Type 2 cement hardens more slowly than type 1 and consequently has a lower strength during the early period of its hardening.

Type 3: This is a cement having high-early-strength properties which is recommended for concrete placed in very cold weather or for any use for which high early strength is desirable, and when the use of this cement is more satisfactory or more economical than the use of a concrete mixture with an unusually high proportion of type 1 cement.

Type 4: This is a special cement having low heat-of-hardening properties. It is designed for use in very large masses of concrete in which slow development of early strength is not detrimental and low heat development during hardening is important. This cement is of limited use and is not generally available in stock.

Type 5: This is a special cement with high sulfate resistance. Its use is recommended only in concrete exposed to severe sulfate action, such as is the case in some western states having soils or waters of high alkali content. Its slow rate of hardening requires a longer period of moist curing than either type 1 or type 2. This cement is of limited use and is not generally available in stock.

Air-entraining Portland Cements. These cements contain from 0.01 to 0.05 per cent by weight of an organic foaming agent, such as a natural resin or acid fat, which is added during grinding of the clinker. During mixing of the concrete, air-entraining cements introduce air into the concrete which gives it certain desirable properties that are discussed in the following chapter on "Concrete." Specifications for such cements were first issued by the A.S.T.M. in 1942. Current specifications of the A.S.T.M. recognize three types of air-entraining portland cements (types 1A, 2A, and 3A), while Federal specifications recognize five types (types 1A, 2A, 3A, 4A, and 5A). These correspond respectively to the various types which do not contain the air-entraining agent and are used where air entrainment is desired in addition to the other properties of a particular type. The chemical requirements of the various types of air-entraining portland cements are the same as those of their non-air-entraining counterparts but their strength requirements are lower.

Selected References for Further Study

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Questions

1. What is the general property of cementing materials which makes them useful in structures?

2. Describe briefly the production of gypsum.

3. What are the general uses of gypsum as a structural material?

4. Why are gypsum blocks made larger than ordinary bricks?

5. How does gypsum act as a fireproofing material?

6. What is the average strength in compression of carefully made gypsum? Of the strongest gypsum compound reported?

7. What are some factors affecting this strength?

8. Outline the process of producing quicklime.

9. What is hydrated lime? For what use?

10. What is natural cement? Pozzuolana cement?

11. Can lime mortar be used under water?

12. Can natural cement mortar be used under water?

13. Define portland cement.

14. From what is it made?

15. Draw a diagram showing the general scheme of a portland-cement manufacturing plant.

16. In your county name structures in which some of the special portland cements have been, or should have been used. State reasons for your answer. If ordinary portland cement was used in any of these structures, has the concrete given good service?

17. Would you use high-early-strength cement for building a large dam? For making concrete blocks? For a concrete highway slab? For a long-span concrete arch bridge? For a highway culvert? Give reasons in each case.

18. How is portland cement air-entrained? What desirable properties are improved by air-entraining? Name a structure in which you would use concrete made with air-entrained portland cement. (Suggestion, look ahead to the last twelve pages of the next chapter.)

CHAPTER XV

CONCRETE

By Harrison F. Gonnerman[1]

Portland Cement Concrete. Concrete consists of a mixture of cement, water, and noncementing or inert materials such as sand, in combination with gravel, crushed stone, or air-cooled iron-blast-furnace slag. The cement and water form a paste or glue which upon hardening holds the mass firmly together. Portland cement, because of its uniformity, reliability, and strength, is generally used as the cementing material in making concrete. Natural, pozzuolana, portland-pozzuolana, and portland-blast-furnace slag cements are used to a very limited extent, generally in special kinds of work.

Portland cement is seldom used alone for structural purposes since such construction would be too costly and, moreover, the cement after hardening might show a tendency to crack, owing to excessive shrinkage. Therefore, in order to produce an economical and durable building material, the cement is generally combined with a relatively large proportion of inert material, called *aggregate.*

Plain and Reinforced Concrete. Concrete is a rather brittle material and, like nearly all brittle materials, is much stronger in compression than in tension. Its tensile strength is relatively low and is usually neglected in design calculations of concrete structures. Concrete construction in which concrete is used without reinforcement, or reinforced only for shrinkage and temperature changes, is known as *plain concrete.* Plain concrete is used for massive work or for parts of structures carrying only compressive load. Heavy foundations and walls, massive dams, arches, and piers, furnish examples of plain concrete construction.

Where tensile stresses exist in concrete structural members, the strength to resist them is furnished by steel bars embedded in the concrete. Such construction is known as *reinforced concrete. Prestressed concrete* is a form of reinforced concrete in which high-strength steel reinforcement is put under an initial stress either prior to the placement of the concrete or after it has been placed and has hardened. The objective is to induce precompression in the concrete where needed to counteract

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tensile stresses produced by external loads. Because of this precompression, prestressed concrete does not normally crack even at loads considerably above the design load. As long as cracking is absent, the concrete behaves structurally as a homogeneous material in the sense that all of the concrete is effective in resisting stresses. Consequently, many advantages are gained, among which are a considerable saving in both steel and concrete, a reduction in diagonal tension stresses, and deflections which are elastic and relatively small within the design-load range.

Some of the principal examples of the uses of reinforced concrete are beams, columns, footings, floor and roof slabs, bridges, reservoirs, tanks, chimneys, light arches, and retaining walls. Reinforcing steel is sometimes used in pavements to hold the edges of cracks tightly together and prevent their opening. The somewhat complex mechanics of reinforced-concrete structures will not be taken up in this book.

Properties Desired in Concrete. The properties which are generally most desired in concrete are durability, watertightness, strength, and resistance to abrasion or wear.

To be durable, concrete must have the ability to resist the destructive forces to which it may be exposed. For example, concrete in pavements, dams, and other exposed structures in northern climates must be able to resist alternate freezing and thawing. Concrete exposed to sulfate and sea waters must be able to resist the action of the chemical salts in these waters. Concrete for certain types of structures where safety from fire is desired must be heat-resistant to a high degree. Watertightness is a most important requirement for concrete that must withstand the destructive effects of severe weathering and is of importance also in concrete dams, tanks and reservoirs, conduits, and other structures subjected to water pressure. It is obvious that strength is an essential property where concrete is used for load-carrying structures. Concrete in pavements, sidewalks, and floors must be resistant to wear in order to withstand the abrasive action of traffic.

Investigations have shown that the basic principles of making concrete are the same, regardless of the type of structure involved. Thus, the same problems which enter into the fabrication of the concrete for an office or factory building are also involved in the design of the concrete mix for a massive dam or for a pavement.

Materials for Concrete. Since the quality of concrete is largely determined by the quality of the materials used in its fabrication, it is important that careful attention be given to their selection. The most important ingredient of concrete is the cement, since it is the cement paste which binds the aggregate particles together. Normal (type 1)

portland cements are most widely used in concrete construction. To meet certain special conditions, modifications of normal portland cement, having special properties, have been developed. These special properties include air-entrainment, high early strength, high resistance to attack by sulfate waters, and low or moderate evolution of heat during hydration. Present-day portland cements are manufactured under rigidly controlled conditions to meet definite minimum requirements such as those of the Standard Specifications of the A.S.T.M. and of the United States Government. The requirements of these specifications are such that they assure high-grade products, and cements meeting these requirements may be considered acceptable for use in all of the usual concrete structures in their respective fields.

Any water that is suitable for drinking may be used for mixing concrete. Acid waters and waters containing considerable amounts of salt should be avoided since they reduce concrete strength.

The aggregates used in making concrete should be of suitable quality. The use of poor aggregates may result in unsatisfactory concrete even though the cement paste is of good quality. In general, the qualities which are desired in materials to be used as aggregate in concrete are durability, cleanness, hardness, toughness, and strength. For some uses the qualities of hardness, toughness, and strength may be waived in order to secure a concrete having special properties such as light weight, low heat conductivity, or good sound absorption.

Classification of Aggregates. For convenience, aggregates are commonly separated into two classes according to their size, the basis for separation being the No. 3 or 4 sieve. That portion of the material having particles ranging in size from the smallest dust particles to particles about ¼ in. in diameter is called *fine aggregate.* The portion consisting of particles ranging from ¼ to 1½ in. or more in diameter is called *coarse aggregate.*

Fine Aggregates. The fine aggregate should be selected with care because of its important effect on the workability, uniformity, strength, durability, and other properties of the resulting concrete.

The three principal considerations involved in the selection of fine aggregate for concrete are (1) composition and structural characteristics of the particles, (2) cleanness of particles and freedom from injurious amounts of deleterious substances, and (3) size and grading of particles. Materials commonly used as fine aggregate in concrete are natural sands, artificial sands prepared by crushing natural stones or air-cooled iron-blast-furnace slag, and lightweight materials such as burnt shale, cinders, pumice, or expanded slag.

Natural sands are used more extensively than any of the other fine

aggregates. Most sands for concrete are obtained from beds of rivers and lakes and from glacial deposits. Since they have been formed by the weathering of rock masses, they consist of a variety of rock material. The sand particles are frequently called upon to withstand repeated wetting and drying, freezing and thawing, or attack by other destructive agencies; hence they must consist of structurally sound, durable minerals. Careful tests have shown that sands having rounded particles are as suitable for fine aggregate in mortar and concrete as sands having sharp, angular particles.

On projects where suitable natural sands are not obtainable, fine aggregates are sometimes prepared by crushing natural rocks and screening the crushed materials to the desired size. When these so-called "stone sands" are used as fine aggregate, they should be free from excessive amounts of dust and the particles should be approximately cubical in shape, since particles which are thin, flat, and elongated decrease workability and increase the water requirement of the concrete.

Lightweight fine aggregates are used extensively in concrete masonry units and in parts of structures where it is desired to reduce weight. Asbestos fibers are used with portland cement in the manufacture of shingles, flat and corrugated sheets, and pipe. Sawdust, wood fibers, perlite,[1] and mica expanded by heating, are sometimes used as aggregate to produce a lightweight concrete for insulating purposes.

Portland cement, when intimately mixed with about nine parts pulverized soil by volume and brought to a predetermined moisture content and then compacted to a predetermined density, upon hardening produces a *soil-cement* paving material that is suitable for light-traffic roads, streets, airport runways, and for many other uses.

Coarse Aggregates. Gravel, crushed stone, and air-cooled iron-blast-furnace slag are used in large quantities for coarse aggregate. Other materials, such as burnt shales, expanded blast-furnace slags, cinders, and shells make satisfactory coarse aggregate for some types of construction. Coarse aggregates, like fine aggregates, must consist of sound, durable inert particles if the concrete is to be strong and weather-resistant. In most localities there are sources of aggregate which have long been in use and which are known to furnish dependable aggregate material. Aggregates from such sources need not be given special tests to determine their suitability. When, however, new sources of supply are to be opened it is desirable that tests for strength, soundness, and other properties be made.[2]

[1] A pearly volcanic glass, to be distinguished from pearlite in steel.

[2] Tests commonly applied to determine the soundness of aggregates are those given in A.S.T.M., C88, "Soundness of Aggregates by Use of Sodium Sulfate or Magnesium

Concrete is frequently given a special name, depending on the kind of aggregate used. Thus we have crushed-stone concrete, gravel concrete, cinder concrete, blast-furnace slag concrete, lightweight aggregate and rubble or cyclopean concrete (concrete in which part of the aggregate consists of pieces of unbroken rock, sometimes several feet in diameter).

Desirable Gradings of Aggregate. In order to produce a workable, compact, homogeneous, and economical concrete it is necessary to use a mixture of fine and course aggregate. A mixture of fine aggregate, cement, and water only is known as *mortar*. To obtain the best results in concrete it is essential that both fine and course aggregate be *well graded*. An aggregate is considered to be well graded when it contains particles ranging in size from the finest to the largest, or coarsest, preferably with the coarser particles predominating.

The size and grading of the fine aggregate are important only as they affect workability[1] and the quantity of water required for a given consistency. Less mixing water is required for coarse, well-graded sands than for the same quantity of fine or of poorly graded sands, but a smaller quantity of fine sand is required in a mix for a given workability. Sand should contain sufficient fines (fine particles) to ensure a smooth-working mixture, preferably 10 to 30 per cent passing the 50-mesh sieve and 2 to 10 per cent passing the 100-mesh sieve; in rich mixes, in air-entrained concrete, or in concretes for certain special uses, the minimum percentages may be reduced somewhat. In some cases it may be economical to use poorly graded sand, otherwise suitable, making up deficiencies in grading by an increased cement content. The practice in some localities is to mix (blend) sands or to use powdered admixtures to improve grading; the major function of powdered admixtures is to provide or increase the fines, particularly in mixes of low cement content.

The coarse aggregate should also contain a range of sizes from ¼ in. up to the maximum size. Considerable variation may occur in the percentages of the various sizes without materially affecting the suitability of the grading so long as the range in sizes is maintained. In general, the combination of sizes producing the lowest void content is considered

Sulfate." The tests consist essentially of alternately immersing sized and weighed samples of aggregate in a saturated solution of either sodium or magnesium sulfate at 21 ± 1°C (70 ± 2°F.) for 18 hr. and drying to constant weight in an oven at 105 to 110°C. (221 to 230°F.). Aggregates which exhibit appreciable disintegration after five repetitions of this treatment are not considered to be satisfactory for use in concrete structures exposed to weathering, unless concrete made from similar aggregate from the same source has been exposed to natural weathering for a period of at least 5 years without appreciable disintegration.

[1] Workability is that property of concrete which permits it to be readily placed and molded without segregation or honeycomb, producing a uniform, homogeneous mass.

best. The maximum size should be as large as can be easily placed Specifications usually limit the maximum size to one-fifth the narrowest dimension of the form and to from two-thirds to three-fourths of the minimum clear spacing between reinforcing bars.

The mixture of fine and coarse aggregates should be so graded that there is not too great a difference in size between the largest sand particles and the smallest coarse-aggregate particles. On the other hand, excessive overlapping of sizes is undesirable.

Undesirable Ingredients in Aggregates. Only clean, uncoated aggregates should be used if best results are to be obtained. Much of the trouble experienced with faulty mortar or concrete is due to the presence of undesirable ingredients in the aggregates. Aggregates should not contain injurious amounts of deleterious substances such as organic impurities, loam, clay, silt, dust, shale, coal, lignite, mica, and soft or rotten particles. Neither should they contain injurious amounts of minerals that will react with components of the cement to produce excessive expansion.

Vegetable loam is particularly objectionable in concrete sands as it carries organic compounds which reduce the strength of concrete and retard or destroy the setting properties of the cement. Sands suspected of containing organic matter should be carefully tested before use.[1]

Most specifications limit the amount of dust, silt, or clay in sands to be used for concrete to about 3 per cent by weight. While slightly higher percentages make for improved workability, some such limit is desirable since these finely divided materials tend to float to the surfaces of the concrete during the placing and finishing operations, forming undesirable laitance seams and producing surfaces which scale and which are not resistant to wear or weathering. Shale particles in quantity are particularly objectionable in aggregate since they break up completely upon exposure to weathering. Chert particles which crack and split upon weathering are also objectionable. Lignite, coal, and soft or rotten par-

[1] A simple test for detecting the presence of organic impurities in sands, known as the "colorimetric test," which may be used in the laboratory or in the field is described under A.S.T.M. "Standard Method of Test for Organic Impurities in Sands for Concrete," C40. In the field this test may be carried out as follows: Fill a 12-oz. graduated prescription bottle to the 4½-oz. mark with the sand to be tested. Add a 3 per cent solution of sodium hydroxide (NaOH) until the volume of the sand and solution, after shaking, amounts to 7 oz. Shake thoroughly and let stand for 24 hr. Observe the color of the clear liquid above the sand. If the solution resulting from this treatment is colorless, or has a light yellowish color, the sand may be considered satisfactory, in so far as organic impurities are concerned. On the other hand, if a dark red or black solution is produced, the sand should not be used unless tests for strength in a mortar or concrete show that it will have no adverse effect.

ticles should not be permitted in considerable quantities since they reduce strength and are easily weathered. Mica is an injurious ingredient in sand or crushed stone for concrete, and aggregates containing considerable amounts of mica should not be used for important structures. Aggregate particles should not be coated with dust, clay, or other adherent materials since these weaken the bond between the particles and the cement paste.

The Standard Specifications for Concrete Aggregates of the A.S.T.M., C33, place the following limitations on deleterious substances and organic impurities:

Deleterious Substances. The amount of deleterious substances in fine or coarse aggregate shall not exceed the following limits:

Item	Maximum per cent by weight of total sample	
	Fine aggregate	Coarse aggregate
Clay lumps	1.0	0.25
Soft particles	....	5.0
Chert which will readily disintegrate (soundness test, 5 cycles)	....	1.0
Material finer than No. 200 sieve	....	1.0[1]
(*a*) Concrete subject to abrasion	3.0[1]	
(*b*) All other concrete	5.0[1]	
Saturated-surface-dry material floating on liquid having a specific gravity of:		
2.0 (material coarser than No. 50 sieve)	0.5[2]	
2.0	....	1.0[2]

[1] If the material finer than the No. 200 sieve consists of the dust of fracture, essentially free from clay or shale, these limits for fine aggregate may, in the case of manufactured sand, be increased to 5 and 7 per cent, and the limits for coarse aggregate may be increased to 1.5 per cent.

[2] This requirement does not apply to manufactured sand produced from blast-furnace slag nor to blast-furnace slag coarse aggregate.

Fine and coarse aggregates shall be free from injurious amounts of material which could react harmfully with alkalies in the cement. If such materials are present in injurious amounts, the aggregate shall be rejected or be used with a cement containing less than 0.6 per cent alkalies, calculated as sodium oxide, or with the addition of a material which has been shown to inhibit undue expansion due to the alkali-aggregate reaction.

Organic Impurities. Fine aggregate shall be free from injurious amounts of organic impurities. Aggregates subjected to the colorimetric test for organic impurities and producing a color darker than the standard shall be rejected unless they pass a specified mortar strength test, or unless the discoloration is due

principally to the presence of small quantities of coal, lignite, or similar discrete particles.

The foregoing values are, in general, reasonable limitations on undesirable ingredients in aggregate. If it is necessary because of unavoidable, local conditions to use an aggregate containing undesirable ingredients, the concrete should be made richer in cement.

Proportioning Materials for Concrete. The problem that confronts the engineer in proportioning the cement, water, and aggregate for concrete is to produce from the available materials, with the least expenditure for materials and labor, a workable concrete, which when hardened will possess certain definite physical properties. The properties desired in the concrete are governed by the service for which it is intended. In concrete for roads, durability, flexural strength, and resistance to abrasion are desired. For prestressed and some other structural members, concrete of high strength is desired, while concrete for dams, reservoirs, and tanks must be strong and durable and, in addition, must be resistant to penetration of water.

The cement is usually the most expensive ingredient in concrete; hence, from the standpoint of economy, it is desirable to use as little cement as possible. By properly proportioning the cement, water, and available aggregates it is often possible to effect considerable savings and still produce a concrete which will fulfill all the requirements for durability, strength, abrasion, and watertightness.

In any mass of sand, gravel, or broken stone there are spaces between the individual particles called *voids*.[1] In workable concrete the voids are well filled and the surfaces of the individual particles are thoroughly

[1] When the bulk specific gravity S and the weight per cubic foot W of the dry material are known, the per cent voids P may be computed from the formula

$$P = 100\left(1 - \frac{W}{62.4S}\right).$$

The following table from Taylor and Thompson's "Concrete, Plain and Reinforced" gives average values of specific gravity for various concrete aggregates:

Material	Specific gravity	Material	Specific gravity
Sand	2.65	Limestone	2.60
Gravel	2.66	Trap	2.90
Conglomerate	2.60	Sandstone	2.40
Granite	2.70	Bituminous cinders	1.50

coated with cement paste, the binding medium. With different types and gradings of aggregates there is a wide variation in the amount and quality of cement paste required to fill all the voids and coat the individual particles when proportions and consistencies are maintained constant. The voids in coarse aggregates graded from ¼ to 1½ in. will generally range from 35 to 50 per cent of the volume of the aggregates. The voids in the usual sands range from 28 to 40 per cent, depending on the grading of the sand and the amount of moisture it contains. Well-graded dry mixtures of fine and coarse aggregates which contain a wide assortment of individual particles may have voids as low as 20 per cent. Aggregates in which the individual particles are of approximately the same size have a much larger percentage of voids than well-graded aggregates.

Because of the smaller quantity of water required, well-graded aggregate in general makes stronger concrete for a given consistency and proportion of cement than does an aggregate in which the fine and coarse particles are nearly uniform in size. It rarely happens that natural mixtures of sand and gravel as found in banks and gravel pits have such proportions of fine to coarse as will make the best grade of concrete. Consequently for most work it is necessary to screen the aggregate materials and then recombine them in such proportions as will give a well-graded mixture.

Methods of Proportioning Materials for Concrete. Several methods have been employed by engineers to determine the amount of the constituent materials to use in order to produce economically a concrete of acceptable quality. Some of these are (1) arbitrarily selected volumes, (2) voids in aggregate, (3) Fuller's maximum-density method, (4) Edward's surface-area method, (5) Talbot's mortar-voids method, (6) Abrams' fineness-modulus method, and (7) trial-batch method. The last two methods use the water-cement ratio—the ratio of the volume of mixing water to the volume of cement in a concrete mixture—as the basis of concrete quality.

Proportioning by Arbitrarily Selected Volumes. This is one of the oldest methods. By this method such mixes as 1–1½–3 (1 part cement, 1½ parts fine aggregate, 3 parts coarse aggregate), 1–2–3½, 1–2½–4, and 1–3–5 by volume are arbitrarily chosen. It was formerly assumed that for workable concrete a quantity of fine aggregate equal to about 50 per cent of the volume of coarse aggregate was required. Subsequent experience has demonstrated that, except in mixtures rich in cement, a larger proportion of fine aggregate is necessary. For well-graded aggregates, the following proportions by dry, loose volume will generally meet the requirements of the types of construction indicated:

Columns or other structural members carrying unusually high compressive stress. Structures exposed to severe weathering conditions	1-1½-3
Floor slabs, beams, and other structural members carrying ordinary stresses and not exposed to severe weathering	1-2-3½
Filling and massive work not exposed to severe weathering	1-3-5

Large differences in results may be obtained by this method if care is not used in handling and measuring the materials, especially if varying consistencies are permitted. Because of differences between aggregates, lack of uniformity in the grinding of given aggregates and lack of control of one of the most important constituents of concrete—the mixing water—this method is frequently not so economical nor does it give so workable or so uniform a concrete as other methods in which the materials are proportioned more scientifically. A serious weakness of this method is the tendency to use excessive quantities of water to overcome harshness resulting from too small a proportion of fine to coarse aggregate or from poorly graded aggregates.

Proportioning by Voids in Aggregate. This method is used only occasionally. After determining the voids in the fine and coarse aggregate, an amount of cement slightly in excess of the voids in the sand and an amount of sand 5 to 15 per cent greater than the voids in the coarse aggregate are used in order to fill all the voids in the final mixture. Several factors tend to render this method of proportioning uncertain. The volume of voids in the fine aggregate is greatly influenced by the amount of contained moisture. Both fine and coarse aggregates vary in compactness, owing to different methods of handling. The amount of the spreading action of the cement paste and sand particles when mixed with coarse aggregate cannot be anticipated in making preliminary void determinations.

In either of the foregoing arbitrary methods, failure to obtain a dense combination of mixed aggregates requires the use of a greater volume of cement paste to obtain the necessary workability. If the volume of paste is increased by using additional cement, the cost is increased; if by using additional water, as is commonly done, the quality is seriously impaired.

The following methods were developed along scientific lines and are based on experimental data:

Fuller's Maximum-density Method. Tests were made by W. B. Fuller and Sanford E. Thompson in 1903 and 1904 for the purpose of determining the combination of sizes of fine and coarse aggregate particles which when mixed with a given percentage of cement by weight produces the densest and most impermeable concrete. This was probably the

first attempt made in this country to employ sieve analysis of aggregates in proportioning concrete. Several hundred different sieve-analysis curves[1] were tested to determine the curve corresponding to densest mix. It was found that the curve of the mixed aggregate and cement which produced the densest, strongest, and most impermeable concrete resembled a parabola and consisted of a combination of an ellipse and a straight line. By careful grading of the aggregates, this method gives a strong concrete but, because of the cost of screening and handling aggregates, may not be economical. This is especially true if large quantities of certain sizes must be wasted to produce the desired grading. The method tends to give harsh-working mixtures and considers only indirectly a very important factor in the design of concrete mixtures—the quantity of mixing water.

Surface-area Method. L. N. Edwards in 1918 presented data of tests on mortars and concretes as a basis for a method of proportioning which he termed the surface-area method. This method assumes that the strength and other properties of mortars and concretes are mainly dependent upon the amount of cementing material used in relation to the total *surface area* of the aggregates. The method has been tried out on some important work but has not been generally adopted. It has some points in common with the fineness-modulus method described later.

Talbot's Method by Voids in Mortar and Concrete. A method of proportioning was presented in 1921 in a paper before the A.S.T.M. by Prof. A. N. Talbot of the University of Illinois. The basis for the method was later given in considerable detail in *University of Illinois Engineering Experiment Station Bulletin* 137 by A. N. Talbot and F. E. Richart. This method does not require sieve analyses of the aggregates but is based on experimental and analytical considerations of the voids in mortar and concrete. In the above-mentioned bulletin, data of numerous mortar and concrete tests are given to show that the strength of concrete is dependent upon the ratio of the absolute volume of the voids to the absolute volume of the cement in a unit volume of freshly mixed concrete. The relation holds when the voids in coarse aggregate are completely filled with mortar and also when not completely filled except in the more extreme cases. When the voids in the concrete are entirely filled with water, the voids-cement ratio and the water-cement ratio are identical, provided the quantity of cement is expressed the same way in both cases. The principles underlying this method of proportioning have been applied by some engineers to the design of concrete mixes for highways as well as for other types of structures.

[1] A sieve-analysis curve is one plotted with size of sieve opening as one coordinate and percentage of material passing (or sometimes percentage retained) as the other.

Fineness-modulus Method. Another method of proportioning, proposed by D. A. Abrams and based on his water-cement ratio principle described in a later paragraph, is the fineness-modulus method. Sieve analyses of the aggregates are made and from these, grading factors designated as fineness moduli[1] are determined. The assumption is that mixed aggregates having the same fineness moduli require the same amount of mixing water to produce concretes of a given consistency and give the same strength so long as the aggregates are not too coarse. From the fineness-modulus determinations the approximate mixes for various consistencies and water-cement ratios may be found from charts based on many laboratory tests. The tests upon which these charts were based covered a relatively narrow field of aggregates. Since, in general, natural sands and gravels, as well as the usual run of crushed rock, are reasonably well graded, the charts have been used successfully in many instances. In some cases, however, where the aggregate gradings were not favorable, blind adherence to the proportions given by the charts has resulted in concrete of unsatisfactory workability. The charts are useful in comparing aggregate materials of different gradings and in studying the interrelation of mix, consistency, grading, and strength. Since the method necessitates sieve analyses and some involved computations it is not so easy to apply as the trial-batch method which is based on the same fundamental principle.

Effect of Quantity of Mixing Water. Several of the methods of proportioning described above do not take into account, except indirectly, the amount of mixing water, which has been found to have a very marked effect on the properties of concrete. As stated previously, concrete is a mass of inert aggregates held together by a hardened paste of portland cement and water. The paste is the active ingredient and the quality of the concrete, as far as proportioning is concerned, is determined largely by the quality of the paste, which in turn is fixed by the relative proportion of water to cement in the paste. Since only a relatively small amount of water can combine with the compounds of the cement, all water in excess of this amount dilutes the paste and reduces its strength, watertightness, and durability. As has been stated, the ratio of the volume of mixing water to the volume of cement in a concrete mixture is known as the *water-cement ratio*. This ratio is commonly

[1] The fineness modulus is the sum of percentages in the sieve analysis divided by 100 when the sieve analysis is expressed as cumulative percentages coarser than each of the sieves in a specified series. The sieve analysis is made with the following U. S. Standard square-mesh sieves, each sieve having a clear opening one-half that of the preceding sieve: 3 in., 1½ in., ¾ in., ⅜ in., No. 4, No. 8, No. 16, No. 30, No. 50, and No. 100.

expressed in terms of U. S. gallons of water per sack of cement, although it is sometimes expressed on a weight basis.

Many series of tests carried out by D. A. Abrams at the Structural Materials Research Laboratory, Chicago, and confirmed by tests of other investigators, have demonstrated the fundamental influence of the quantity of mixing water on the strength of concrete. Figure 82 shows the general relation between compressive strength and water content as determined by Abrams. It is based on the results of an extensive series of laboratory tests made during 1917–1918 with portland cement

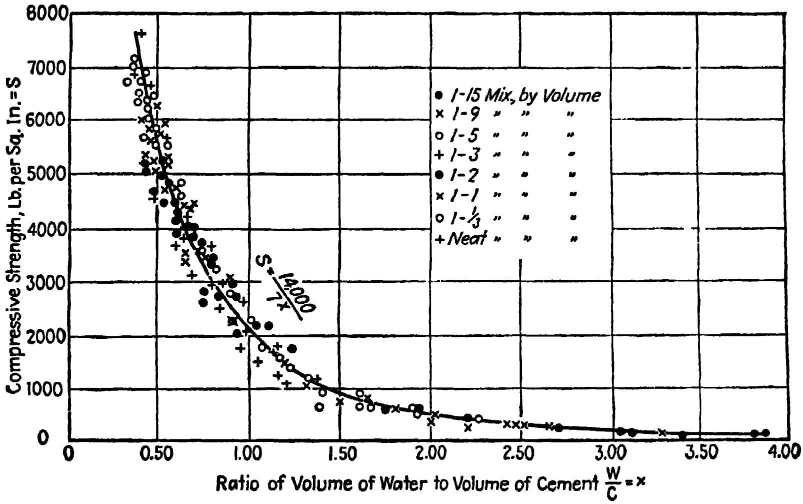


FIG. 82. Relation between compressive strength of concrete and water-cement ratio. Twenty-eight-day tests of 6- by 12-in. cylinders. (*Courtesy of D. A. Abrams.*)

representative of that manufactured at the time. Present-day normal portland cements give very much higher 28-day strengths than those shown by the curve in Fig. 82.

The data given in Fig. 82 cover a wide range of mixes and for each mix, except the neat cement, the maximum size of the aggregates used ranged from that which passed a 14-mesh to that which passed a 1½-in. sieve. Furthermore, for all mixes and gradings there was a wide variation in the amount of water used. The water content of the concretes represented in Fig. 82 is expressed as a ratio of the volume of cement used, 1 cu. ft. of cement being considered to weigh 94 lb. The legend given in the diagram serves to distinguish the various mixes, but no distinction is made either between the aggregates of different maximum size or between the different consistencies used. The data for dry concretes or concretes which were not easily workable are not included

in the diagram. If the data for these concretes had also been plotted, a series of curves (similar to the curve shown in Fig. 82) extending downward and to the left from the main curve would have been obtained.

The fundamental water-cement-ratio relation has been well established and may be briefly stated as follows:

> For plastic mixes using sound and clean aggregates, strength and other desirable properties of concrete under given job conditions are governed by the net quantity of mixing water used per sack of cement.

This relation furnishes a sound and simple basis for designing concrete mixtures for any purpose. Designing a concrete mix by the water-cement-ratio principle consists in selecting the water-cement ratio which will produce concrete of the desired strength and resistance to exposure and then finding the most suitable combination of aggregates which will give the necessary workability when mixed with cement and water in this ratio.

Selection of the Water-cement Ratio. In selecting the water-cement ratio, consideration is given to the strength requirements and to the conditions to which the concrete will be exposed. Table XXX[1] gives values suitable for various conditions of exposure. For structures to be exposed to the weather, these values will generally govern the water-cement ratio to be used since they will normally produce a higher strength than that used in the design. For other structures, the strength requirements will govern the water-cement ratio to be used. Water-cement ratio strength relationships for concretes made with type 1 and with type 3 portland cements are given in Fig. 99.

Proportioning by Trial Batches. Having selected the water-cement ratio, the next step in the design of the mixture is to determine that combination of fine and coarse aggregate which for the selected water-cement ratio will produce a plastic mixture which can be easily placed without segregation and which will remain homogeneous during the setting and hardening period. It is desirable to arrive at those proportions which will give the most economical mixtures consistent with proper placing. The relative proportions of fine and coarse aggregates and the total amount of aggregate that can be used with a given water-cement ratio depend on the consistency required for proper placing and on the type, grading, and surface characteristics of the aggregate.

The consistency required is governed by the conditions under which

[1] Adapted from "Basic Principles of Concrete Making" by Franklin R. McMillan. This table is from the report of the Joint Committee on Standard Specifications for Concrete and Reinforced Concrete.

TABLE XXX. WATER CONTENT* (IN U. S. GALLONS PER SACK OF CEMENT) SUITABLE FOR VARIOUS CONDITIONS OF EXPOSURE

Values based on the assumption that the concrete will be plastic and workable and placed and compacted in such manner that a dense, homogeneous mass will be obtained. They also presume that the concrete will be sufficiently protected from loss of moisture and from low temperatures to ensure that proper hardening will develop

Type or location of structure	Severe or moderate climate, wide range of temperatures, rain and long freezing spells, or frequent freezing and thawing					Mild climate, rain or semiarid, rarely snow or frost				
	Thin sections		Moderate sections		Heavy and mass sections	Thin sections		Moderate sections		Heavy and mass sections
	Reinf.	Plain	Reinf.	Plain		Reinf.	Plain	Reinf.	Plain	
A. At the waterline in hydraulic or waterfront structures or portions of such structures where complete saturation or intermittent saturation is possible, but not where the structure is continuously submerged.										
In sea water	5	5½			6	5	5½			6
In fresh water	5½	6			6½	5½	6			6½
B. Portions of hydraulic or waterfront structures some distance from the waterline, but subject to frequent wetting:										
By sea water	5½	6			6	5½	6½			7
By fresh water	6	6½			6½	6	7			7½
C. Ordinary exposed structures, buildings and portions of bridges not coming under above groups	6	6½			7	6	7			7½
D. Complete continuous submergence:										
In sea water	6	6½			7	6	6½			7
In fresh water	6½	7			7½	6½	7			7½
E. Concrete deposited through water	†	†	5½		5½	†	†	5½		5½
F. Pavement slabs directly on ground:										
Wearing slabs	5½	6	†		†	6	6½	†		†
Base slabs	6½	7	†		†	7	7½	†		†
G. Special cases:										

(a) For concrete exposed to strong sulphate ground waters, or other corrosive liquids or salts, the maximum water content should not exceed 5 gal. per sack. See Section 600, Report of the Joint Committee.

(b) For concrete not exposed to the weather, such as the interior of buildings and portions of structures entirely below ground, no exposure hazard is involved and the water content should be selected on the basis of the strength and workability requirements.

* In interpreting this table surface water carried by the aggregate must be included as part of the mixing water in computing the water content.

† These sections not practicable for the purpose indicated.

the concrete is to be placed and involves the size and shape of the members, spacing of reinforcing bars and other details which might interfere with the ready filling of the forms. The slump test[1] in Fig. 83 is frequently used as a rough measure of workability. While this test is not an absolute measure of workability, under uniform operating conditions it is useful in revealing changes in grading, proportions, or water content. In order to avoid mixing too stiff or too wet, and to avoid honeycomb or other placing defects, slumps and aggregate sizes falling within the following limits are recommended in the Joint Committee report.

FIG. 83. Measuring slump of concrete.

Portion of structure	Consistency-slump		Maximum size of coarse aggregate, in.
	Maximum, in.	Minimum, in.	
Reinforced foundation walls and footings	5	2	1½
Plain footings, caissons and substructure walls	4	1	2
Slabs, beams, and reinforced walls	6	3	1
Building columns	6	3	1
Pavements	3	2	2
Heavy mass construction	3	1	3–6 *

* In making the slump test, all aggregate larger than 2 in. should be screened out of the mixture.

The limiting slumps given above will need some modification when high frequency vibration is used to compact the concrete.

When the consistency desired has been determined, the proportion

[1] The slump test is made in accordance with the A.S.T.M. "Method of Slump Test for Consistency of Portland Cement Concrete," C143. The apparatus for determining the slump consists of a truncated sheet metal cone with top diameter of 4 in., bottom diameter of 8 in., and height of 12 in. The freshly mixed concrete is placed in the mold in three layers, each layer being rodded 25 times with a bullet-pointed rod ⅝ in. in diameter. After filling, the mold is immediately withdrawn and the slump measured as shown in Fig. 83.

of fine to coarse and the amount of total aggregate to be used can readily be determined by mixing trial batches of concrete until a desirable combination is secured. Small trial batches can be conveniently made using about $\frac{1}{16}$ sack of cement, as this size batch can be mixed by hand in a pan and produces enough concrete for a slump test. The aggregates should be surface dried if possible, so that no correction for absorption or for free moisture in the aggregates will be necessary. First a paste is prepared consisting of the cement and water in the ratio selected from Table XXX, Fig. 97 or 99. Then the fine and coarse aggregates are added until the batch has the consistency desired. Several batches should be tried in order to find the combination of materials which will give the best workability and still produce a good yield of concrete.[1] The important points to decide are total amount of aggregate to use with a sack of cement and the relative amounts of fine and coarse. In

[1] In a plastic mix the yield or amount of concrete obtained from a batch can be calculated either by dividing the total weight of the batch by the weight per cubic foot of the concrete, determined in a suitable measure, or from the absolute volumes of the materials used. The absolute volume is the actual volume of solid matter in a given amount of the material. The volume of solid matter can be calculated from the following relation:

$$\text{Absolute vol.} = \frac{\text{wt. of material}}{\text{bulk sp. gr.} \times \text{unit wt. of water (62.4 lb. per cu. ft.)}}$$

For example, the yield of a 1-2½-3 mix would be calculated as follows, assuming that dry aggregates are used, that the fine aggregate weighs 112 lb. per cu. ft. and the coarse aggregate 98 lb. per cu. ft., that 6 gal. of water per sack of cement is required to give the desired slump after allowing for the water absorbed by the aggregates, and that the fresh concrete had a measured air content of 5 per cent by volume:

$$\text{Absolute volume cement} = \frac{94 \text{ lb.}}{3.15 \times 62.4} = 0.48 \text{ cu. ft.}$$

$$\text{Absolute volume fine aggregate} = \frac{2.5 \times 112}{2.64 \times 62.4} = 1.70 \text{ cu. ft.}$$

$$\text{Absolute volume coarse aggregate} = \frac{3 \times 98}{2.66 \times 62.4} = 1.77 \text{ cu. ft.}$$

$$\text{Absolute volume water} = \frac{6}{7.5} = 0.80 \text{ cu. ft.}$$

$$\text{Volume of solids plus water} = 4.75 \text{ cu. ft.}$$

Since air content = 5%, total volume concrete

$$\text{produced per sack cement} = \frac{4.75}{0.95} = 5.00 \text{ cu. ft}$$

Materials required for 1 cu. yd.:

$$\text{Cement} = \frac{27}{5.00} = 5.4 \text{ sacks}$$

Fine aggregate = $2.5 \times 5.4 = 13.5$ cu. ft.
Coarse aggregate = $3.0 \times 5.4 = 16.2$ cu. ft.
Net water = $5.4 \times 6 = 32.4$ gal.

general, that mix which has the lowest workable proportion of fine aggregate will produce the greatest yield per sack of cement. In order to avoid excessive cost of placing and finishing, however, there must be sufficient mortar to completely embed the coarse-aggregate particles. Figure 84 shows mixes with too little cement-sand mortar, the correct amount of mortar, and too much mortar. When several different aggregates are available, all of which meet the specification requirements, several trial batches can be made to compare their concrete-making properties, with a view to determining the most economical combination. If no trial batches have been made prior to starting the actual construction, the mix can be designed using a full-size batch and mixing

(*a*) Concrete mixture with insufficient mortar to fill all the spaces between the coarse aggregate particles.

(*b*) Concrete mixture with the correct amount of mortar.

(*c*) Concrete mixture with an excess of mortar.

Fig. 84. Concrete mixtures with varied amounts of cement-sand mortar. (*Courtesy of Portland Cement Association, Chicago, Ill.*)

in the job mixer. In either case, adjustments will probably be necessary in the next two or three batches in order to secure the most economical, workable mixture. To meet changing conditions all adjustments are made by varying the amounts of fine and coarse aggregates. The water-cement ratio must be accurately maintained throughout the job, and the resulting concretes must be readily placed.

Measuring Materials for Concrete. When the proportions of the concrete materials have been determined the proper quantities of cement, water, aggregates, and air-entraining agent, if used, for the various batches must be carefully measured in order to ensure a uniform and economical product. Selection of equipment to be used for measuring the concrete materials in a given case depends on the character and extent of the work.

Cement is measured by volume or by weight, a bag of cement which weighs 94 lb. being considered the equivalent of 1 cu. ft. A barrel of cement contains 4 bags. Cement is sometimes bought in bulk, in

which case the amount for each batch is weighed. Aggregates, also, are measured either by volume or by weight.

Common sources of error in measuring sand by volume are failure to take into account variations in moisture content and differences in method of measurement, or both. When moisture is present in sand, the films of water adhering to the surfaces of the particles spread them apart and increase the apparent volume. If the sand is measured by loose volume in the damp condition, the amount of this "bulking" must be determined and corresponding corrections made to the measured quantities. The correction for bulking in volumetric measurement of sand is made by adding a proportionately larger volume of the damp sand to secure any desired volume of dry loose, or dry compacted sand. Fine sands bulk more for a given moisture content than coarse sands. The greatest amount of bulking usually occurs at moisture contents of 4 to 8 per cent and with fine sands may amount to 25 or 30 per cent of the dry volume.

In addition to the bulking due to moisture, there is some variation in volume due to method of measurement: the more a sand is compacted during measurement, the greater the weight in a given volume. Where proportions are specified by volume, measurement of the aggregates is generally based on the unit weight of dry, compacted materials determined in accordance with standard methods of the A.S.T.M.

Where the sand is fed by gravity from a hopper into a graduated volumetric batcher, the degree of compacting is reasonably uniform from batch to batch, and consistent results can be expected. When measurement is by shovels or wheelbarrows, as is common on jobs of small or intermediate size, considerable variation occurs. This variation can be controlled to a certain extent by calibrating the wheelbarrows or by measuring the sand into the wheelbarrows with bottomless boxes of known volume. When sand is weighed, no account need be taken of bulking, and the degree of compacting does not influence the quantities measured.

Volumetric measurement of coarse aggregate is not influenced by moisture content unless the small particles predominate and considerable moisture is present. The degree of compacting, however, may introduce appreciable variations in measurement.

Because of the inaccuracies of volumetric measurement, particularly of sand, measurement by weight is standard practice on all important work. In order to secure greater uniformity in grading, coarse aggregates are frequently weighed in two or more sizes. Typical equipment for batching water, cement, and aggregates is shown diagrammatically in Fig. 85. Automatic weighing and batching equipment is used in many modern

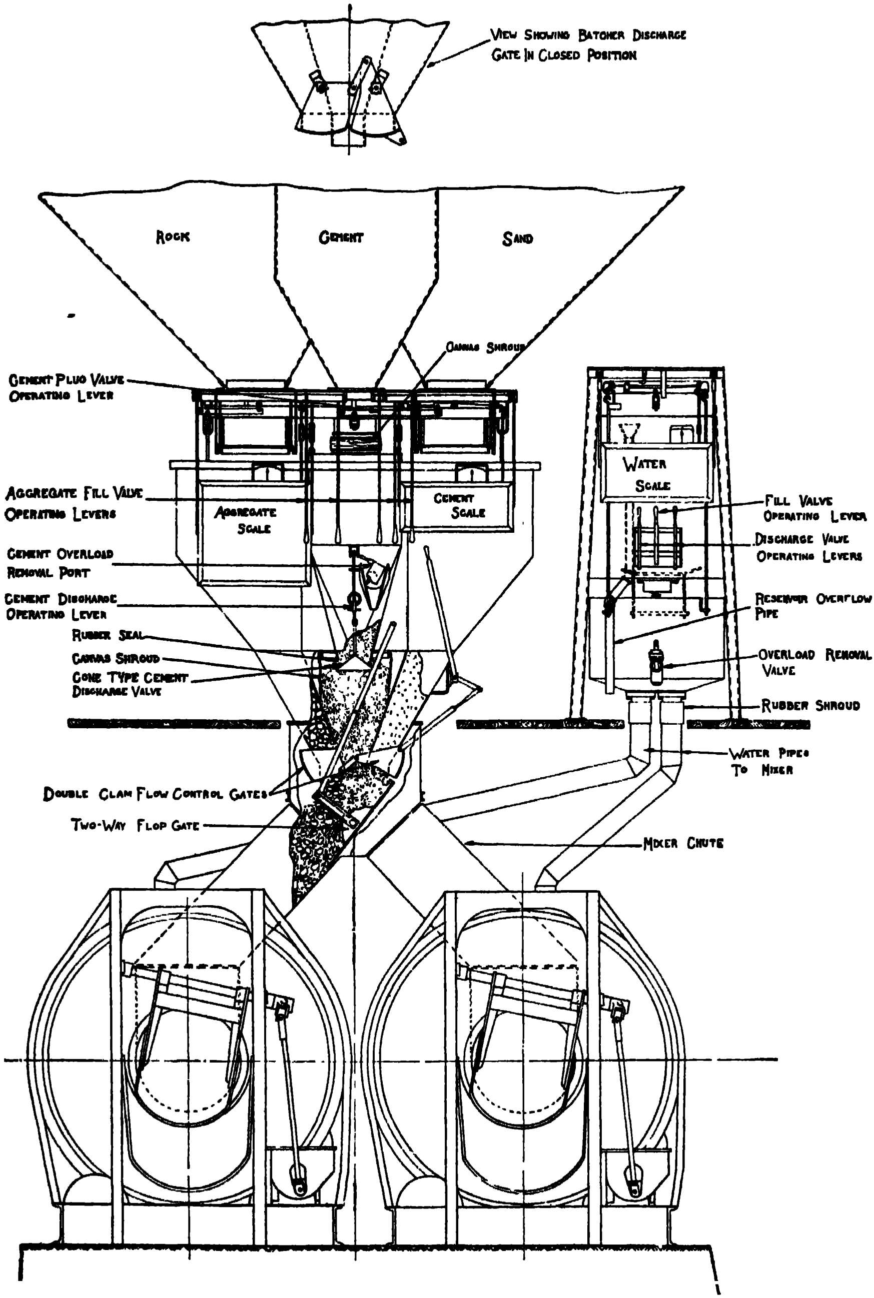


FIG. 85. Diagram showing equipment for batching water, cement, and aggregates. (*Courtesy of C. S. Johnson Company, Champaign, Ill.*)

plants, eliminating to a considerable extent the inaccuracies which often accompany manual control of these operations.

Since the quantity of water in the batch has such a great influence on the properties of the resulting concrete, it is particularly important that the water for the different batches be accurately controlled. The use of the water-cement-ratio method of proportioning has resulted in the development of a number of water-measuring devices which will give satisfactory results if properly handled. Some mixers are equipped with tanks having adjustable discharge pipes or water gages and others with meters. In central or stationary mixing plants, water is frequently measured by weight.

In measuring the mixing water, allowance must be made for the free or surface moisture carried by the aggregates. Sand as delivered on the job is seldom completely dry, the moisture content varying usually from about 3 to 7 or 8 per cent. If this is neglected, an excess of from $\frac{3}{4}$ to 2 gal. of water per sack of cement will be included in the average batch, with consequent reduction in quality. Coarse aggregate as received rarely carries more than 1 or 2 per cent of free water unless it is delivered directly from a barge or a washing plant.

Several methods of determining moisture content have been developed. The simplest consists in drying a small sample by heating. By weighing the sand before and after drying, the amount of moisture can be calculated and allowed for. In field determinations, alcohol can be mixed with the sand and ignited in order to dry it. Other methods are based on the relative displacement in water of wet and dry sand samples of equal weight.

Mixing Concrete. When the materials have been measured in the proper proportions the next step in the manufacture of concrete is to mix them until the aggregate particles are completely coated with cement paste and a homogeneous mixture is obtained. Mixing the ingredients for concrete may be done either by hand or in a power-driven mixer.

Practically all concrete, even for small jobs, is machine mixed in *batch* mixers which range from about 3 cu. ft. to 4 cu. yd. in capacity. Most batch mixers operate on the revolving-drum principle. Materials for the batch are introduced into a revolving drum which is fitted with blades projecting inward. As the drum revolves, the ingredients are carried part way round and turned over as they are dropped to the bottom of the drum. A thorough mixing is thus effected. Batch mixers are usually run for at least 1 to 2 min. after all the materials are in the mixer, the exact time depending on the size and construction of the mixer used and on the richness and consistency of the mix.

Two-compartment drum batch mixers of 34 cu. ft. rated capacity are

sometimes used on large highway projects. With this type of mixer the drum will accommodate two batches simultaneously, which enables a much greater number of batches to be mixed in a given time than when a single batch mixer is used.

Available laboratory tests show that increasing the time of mixing to about 2 min. increases the strength of concrete slightly. Unless this

FIG. 86. Central concrete mixing plant with truck mixers in foreground. The bin has five compartments, four for aggregates and one for cement. (*Courtesy of Blaw-Knox Co., Pittsburgh, Pa.*)

can be done without slowing up the placing operations, it is usually more economical to use other means to increase the strength where such increase is desired. It has also been observed that longer mixing increases the plasticity of concrete mixtures. This is attributed to the more intimate operation of the ingredients and to the increased proportion of very fine aggregate particles produced by abrasion and impact in the mixing process.

In the larger cities, and in many smaller communities, central mixing

plants (Fig. 86) have come into prominence. At central mixing plants the concrete is mixed in large mixers and then dumped into trucks which transport it to the job. These trucks are equipped with agitator bodies which keep the concrete slowly in motion and aid in preventing segregation during transportation. Sometimes the concrete is transferred in dump trucks of special design. In some cases the materials for a batch are measured at a central plant and then loaded on trucks having specially constructed mixer bodies (Fig. 86) which mix the

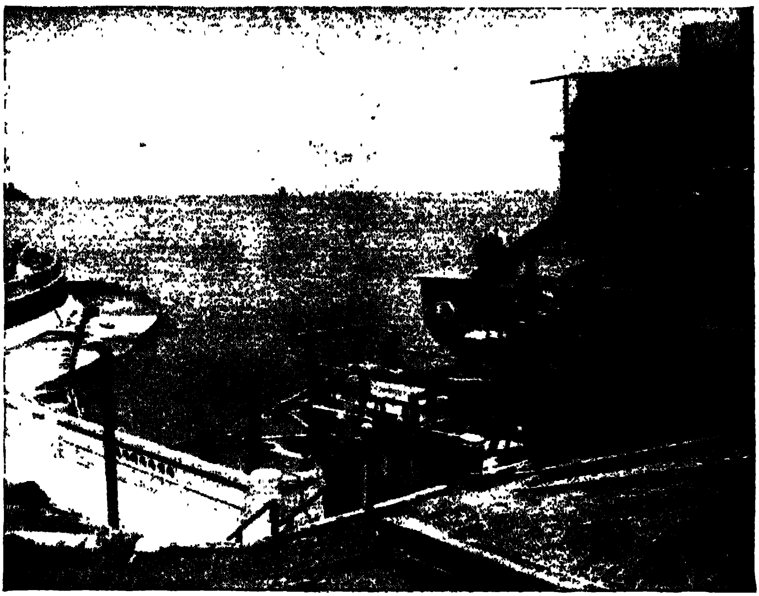


FIG. 87. A 27-E paving mixer set up to discharge the mixed concrete into a concrete pump, which pumps the concrete through a 7-inch pipe to point of placement. (*Courtesy of Chain Belt Co., Milwaukee, Wis.*)

concrete either while in transit or upon arrival at the job. In other cases the concrete materials are plant-mixed before they enter the truck mixer only long enough to "shrink" the batch and thus permit a larger batch to be hauled. Further mixing is accomplished in the truck.

Transporting Concrete. After mixing, concrete should be transported to the place of deposit in such a manner as will prevent segregation of the ingredients. The means of transportation is primarily a question of economy. The important requirement is that the concrete when delivered at the place of deposit shall be of proper quality and uniformity. The type of equipment used has some bearing on the design of the concrete mix, since the concrete must be readily transported. On small structures, wheelbarrows or two-wheel carts are generally used to

transport concrete to the forms. On the larger structures, industrial cars with removable bodies, cableways, conveyor belts, and towers with inclined open chutes are employed. Sometimes concrete is pumped through pipe lines from the mixer to the forms (Fig. 87). In the construction of large dams, depositing by bottom-dump buckets handled by derricks or cableways is a common practice.

A danger to be guarded against in chuting is the tendency to use overwet mixtures in order to cause the concrete to flow down the chutes readily. This practice causes segregation of the ingredients. Owing to this separation and to the fact that excess mixing water has a very harmful influence on strength and other desirable properties, this method of handling often produces concrete which is not uniform and is of decidedly inferior quality. With properly designed mixes and chutes, concrete can be successfully handled without the use of excess water. However, because of the danger of segregation, chuting of concrete over long distances has been discontinued.

Depositing Concrete. Proper placing of concrete in the forms is a most important factor in obtaining durable concrete structures. Before placing, all debris and accumulated water should be removed from the space to be occupied by the concrete.

To secure compact uniform concrete it should be placed in the forms evenly and without separation of the ingredients. Concrete which is of a relatively dry consistency should be placed in layers about 6 or 8 in. in thickness. For wetter consistencies the thickness of the layers may be increased to 12 in. or more, depending on the shape and size of the section being placed. After placing, the concrete is puddled and spaded to remove entrapped[1] air and to aid in securing a compact uniform mixture. The spading tool is run up and down between the form and the fresh concrete, permitting the escape of air and working mortar to the forms, thus giving a smooth finish to the exposed surfaces of the hardened mass. The same result may also be obtained by rapping the forms with hammers or by vibrating with pneumatic or electric vibrators, taking care, however, not to carry this to such an extent as to cause separation of the ingredients.

Concrete should not be deposited at one point and be required to flow to distant points. When concrete flows long distances, segregation occurs and either honeycombed spots or regions containing an excess of fines and water are produced. In order to avoid segregation the concrete should be

[1] Distinction should be made between entrapped air and entrained air. The former consists of relatively large pockets of air produced during mixing or handling. The latter are minute bubbles purposely introduced to improve resistance to frost and to salt action

of plastic consistency, just stiff enough to flow sluggishly when tamped or spaded. If a small amount of water accumulates during placing, it should either be absorbed by gradually stiffening the mix, or be drained to a low spot and removed. A good practice is to overfill the forms, allow the excess concrete to remain in place for about 1 hr., then reconsolidate the concrete by light surface tamping and strike off to the desired elevation. This procedure removes the laitance, eliminates surface checks, and produces a more weather-resistant surface.

Depositing under Water. Where it is necessary to deposit concrete under water, special methods must be used in order to prevent the cement from being washed away and also to prevent segregation of other ingredients. A disadvantage of any method of placing under water is that it is difficult to tell whether the concrete has been properly placed. A tremie is generally used to deposit concrete under water. This consists of a tube about 1 ft. or more in diameter provided with a hopper at the top and a slightly flaring bottom. The tremie is plugged at the lower end, filled with concrete, and then lowered into place with a derrick. The tube is kept full of concrete at all times. To cause a flow of concrete through the tube, the discharge end is raised a few inches at a time but is kept submerged in the newly placed concrete so as not to break the seal. Some tremies are equipped with a valve at the bottom to control the flow of concrete.

Concrete to be deposited under water is sometimes lowered into place in drop-bottom buckets or in loosely woven bags of jute or other coarse cloth. Concrete should not be deposited in flowing or turbulent water since this results in washing the cement from the aggregates. Cofferdams which can be dewatered are frequently used to enclose the space in which the concrete is to be deposited. In general, placing under water should be resorted to only where it is impossible to dewater the space to be occupied by the concrete or where the cost of such dewatering would be prohibitive.

Vibrated Concrete. The use of high-frequency electric or pneumatic vibrators for compacting concrete in the forms has become common practice, particularly on large, massive work. Vibration is essentially a mechanical method of puddling concrete. By this means, mixtures which are harsh and stiff are rendered plastic and while in this condition are consolidated by gravity. On the other hand, mixtures which already possess sufficient plasticity for placing in simple forms are rendered more fluid and can thus be made to flow into inaccessible locations where hand-spading and puddling would be ineffective. Vibration can be applied to the concrete by inserting the vibrator into the mass, by applying a vibrating shoe or screed to the top surface, or by vibrating the forms.

(*a*) Consolidating concrete with internal vibrator.

(*b*) Leveling surface of concrete with vibrating shoe.

FIG. 88. Placing mass concrete with vibrators. (*Courtesy of Electric Tamper and Equipment Co., Ludington, Mich.*)

Internal vibrators are most commonly used and are of two general types. In one type, Fig. 88*a*, the driving moror is housed with the vibrating element, which is inserted into the concrete. In the other type, the vibrating element is actuated through a flexible shaft by a motor which can be moved around at will.

The float or shoe vibrator, illustrated in Fig. 88*b*, is used principally to level off the surface of mass concrete which has been placed very stiff and consolidated by means of internal vibrators.

Vibratory hand screeds have been developed to aid in placing concrete in city pavements, bridge decks, ramps, sidewalks and other types of construction.

Form vibrators are used extensively in the manufacture of precast concrete units such as pipe, joists, building units, and cast stone. They are used to a limited extent for concrete which is cast in place, sometimes in conjunction with internal vibrators to ensure smooth surfaces.

Manufacturers of vibrating equipment have made notable improvements in their products. Simultaneously laboratory and field investigations have been undertaken by various agencies. As yet, however, fundamental information has not been made available by means of which the engineer can choose scientifically the size and number of vibrators and the frequency, amplitude, and duration of vibration to be employed.

It has been demonstrated that frequencies of at least 3,000 vibrations per minute are desirable for effective vibration, and that the effectiveness is increased by increasing the frequency to 5,000 or more vibrations per minute. The duration of vibration required in a given location and the radius of the vibrated zone depend upon the size and the characteristics of the vibrator and upon the characteristics of the concrete mixture. In general, for internal vibration, a period of from 5 to 10 sec. in each location is sufficient, and the vibration is found to be effective for a radius of 12 to 18 in. Thus, if the vibrator is inserted at points approximately 12 in. apart and the vibration continued until the surrounding concrete is consolidated, satisfactory results will usually be obtained.

Bonding New and Old Concrete. When concrete is to be deposited on or against concrete which has hardened, the surface of the hardened concrete is cleaned of all foreign matter and laitance, a light-colored, powdery substance which forms on the surface of concrete where water has accumulated in placing. Laitance can best be removed by the use of wire brushes and a thorough scrubbing of the surface. On mass construction, laitance is sometimes removed by means of a combination jet of compressed air and water, applied within a few hours after placing. After cleaning, the concrete is roughened and wetted with water. The

wetted surface is then thoroughly coated with a wash of neat cement grout, or a rich mortar, before the new concrete is applied.

It is a common assumption that if laitance is completely removed all danger has been eliminated. Appreciable amounts of laitance, however, indicate the presence of excess water, which means that the portion of the concrete immediately beneath the surface will be porous. In such cases the removal of a small layer of laitance may still leave several inches of porous concrete through which water will pass even under moderate pressure. The effect of this porous layer at the top of each day's work can be seen in many structures subject to water pressure. The lower portion of the lift is found to be hard and dense while the upper portion shows efflorescence due to passage of water or disintegration due to frost action.

Finishing Concrete. After concrete is deposited in the forms, the exposed surfaces are finished to the contour and texture desired. The method of finishing and type of finish depend on the use to which the concrete is to be put. In hand finishing, the concrete is struck off by means of a template and a rough finish produced by the use of a wooden float. If a rough surface texture is desired, floating constitutes the final operation. If a smoother finish is required, the floated surface is allowed to stiffen until the water film or sheen has disappeared, after which it is smoothed with a steel trowel.

Concrete pavements are usually finished by machine except where variations in width and grade, as in city streets, make hand finishing more economical. With machine finishing the concrete is distributed on the prepared subgrade in front of a finishing machine (Fig. 89) which spreads the concrete and screeds it to the desired contour. Vibrating rollers or screeds are sometimes used to consolidate the concrete. Following this operation, hand methods are employed to eliminate small irregularities and to obtain the final finish. Frequently a rough texture is imparted by brooming or by dragging a sheet of burlap over the finished surface.

Prior to finishing in some installations, such as floors, it is sometimes the practice to withdraw a considerable amount of the free water from the concrete by applying a vacuum to suction mats placed over the concrete. By this vacuum process the finishing operation is speeded up and a well-consolidated concrete of low water-cement ratio and good wearing qualities is obtained.

Curing. Concrete sets and hardens as a result of the chemical reactions which take place between the compounds of the cement and the mixing water. The process of hardening, which is a result of the hydration of the cement, continues indefinitely at a diminishing rate, as long as

water is present and temperatures are favorable. The action is retarded by low temperatures, and little, if any, hardening can be expected at temperatures below the freezing point of water. Curing therefore consists in supplying moisture and in maintaining favorable temperatures, so that hydration may continue until the internal structure of the concrete is built up to the point where strength or other properties are developed to a sufficient degree to meet the requirements of service.

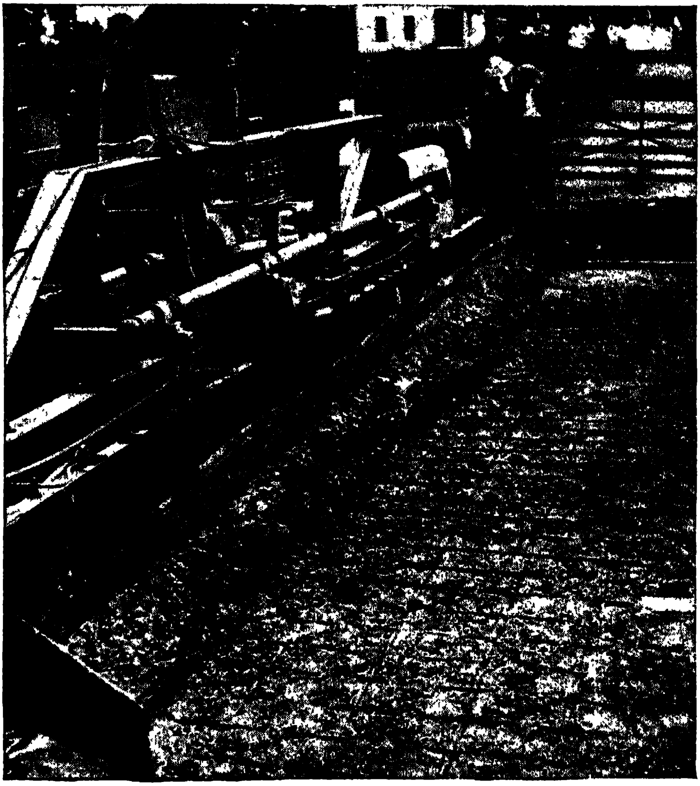


FIG. 89. Concrete-pavement finishing machine.

Concrete as usually mixed contains much more water than is required to hydrate all the cement particles. Hence, if the mixing water is retained in the mass, additional water for curing need not be supplied. An understanding of the part played by the water in a concrete mix may be had from Fig. 90, which shows the relative amounts of each constituent in several concrete mixtures of the same consistency and the relative amounts of each constituent in the cement-water paste of each mixture represented. From this figure it is seen that for any given period after mixing only a part of the water has entered into chemical combination

with the cement. The uncombined or free water, if retained, is available for combination with the unhydrated cement and thus for building up the internal structure of the mass.

The importance of building up the internal structure through continued curing, to the highest possible degree consistent with economy, cannot be too strongly emphasized. If concrete is permitted to dry out too soon after placing, only a relatively small part of the mixing water combines with the cement. The remainder evaporates from the mass with the result that the concrete fails to gain strength at a normal rate with lapse of time. Moreover, with rapid loss of the mixing water, shrinkage stresses are set up which may cause cracks in the concrete before it has hardened sufficiently to resist such stresses. In order, therefore, that the concrete after placing may set and harden properly it is essential that it be protected in some way to prevent it from drying.

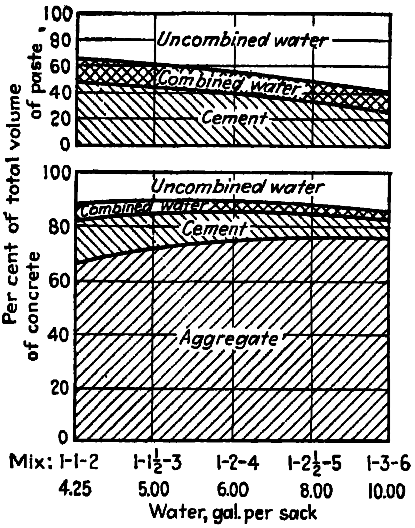


FIG. 90. Composition of concrete mixtures of uniform consistency (slump 3 to 4 in.). (*Courtesy of F. R. McMillan.*)

Methods of Curing. The most satisfactory and certain method of curing is to apply water to exposed surfaces by sprinkling or ponding. Covering with wet earth, burlap, cotton mats, straw, or other suitable materials gives good results provided the coverings are kept wet. Sometimes exposed surfaces are covered with heavy paper, or are coated with paints or chemicals either immediately after the concrete has been finished or after it has hardened. The purpose of these coverings and coatings is to prevent the escape of the mixing water so that it will be available for continued hydration of the cement.

Vertical surfaces are more difficult to cure than horizontal surfaces and may be protected by leaving the forms in place as long as possible or by covering with wet canvas or burlap. Perforated pipes or nozzles which discharge water in such a manner that it will run slowly over the concrete are sometimes employed with excellent results.

The length of the curing period depends on the type of structure, type of concrete, and the climatic conditions existing when the concrete is placed and cured. Under ordinary conditions, concrete should be protected from loss of moisture for at least 5 days. Periods greater than

5 days may be necessary where subsequent conditions will be unfavorable for continued hydration, and somewhat shorter periods may be employed where they are especially favorable or where high-early-strength concrete is used. In hot, dry weather it is necessary to prolong the curing period because of the more rapid evaporation of water from the concrete.

Curing Tests. Thorough curing is a very important factor in developing to a high degree the desirable properties of concrete, such as strength, watertightness, and resistance to wear and to attack by destructive

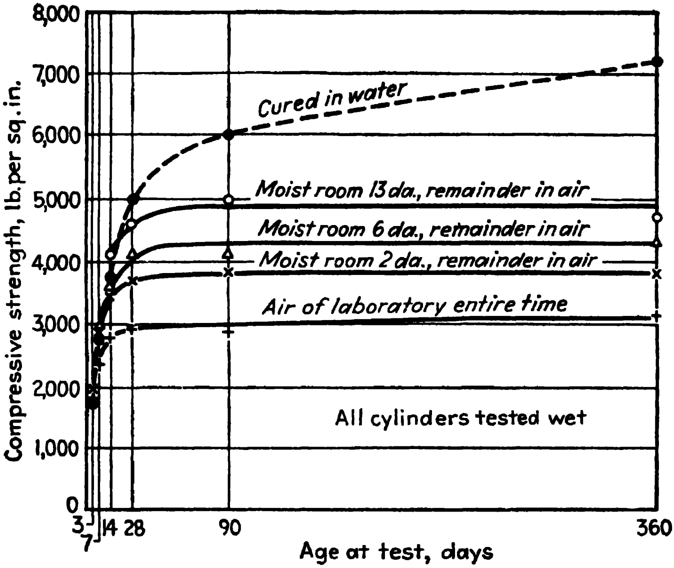


FIG. 91. Compressive strength of concrete cured moist for different periods.

agencies. The curves in Fig. 91 show the marked effect of the duration of moist curing at a temperature of 70°F. on the compressive strength of concrete at ages of 3 days to 1 year. In these tests the water-cement ratio of the concrete was 5.4 gal. per sack. The specimens, which were 6- by 12-in. cylinders, were removed from the molds at 1 day and cured as indicated. In order to eliminate the effect of variable moisture content when the specimens were tested, they were brought to the same degree of saturation by soaking in water for 1 to 7 days before loading.

A gradual improvement in strength occurred at all ages with increase in the duration of moist curing. Concrete cured in air at 50 per cent relative humidity after removal from molds was only about 45 per cent as strong at 1 year as concrete cured continuously in water. Concrete cured 13 days in moist room and then in air of 50 per cent relative humidity was two-thirds as strong at 1 year as that cured continuously in water but was 50 per cent stronger than that cured in air the entire time.

The favorable influence of curing on watertightness of concrete is brought out by the curves in Fig. 92. Each of the three curves in this figure shows a rapid decrease in leakage as the period of moist curing at 70°F. was lengthened. The lower the water content of the concrete the shorter was the period of moist curing required to obtain completely watertight concrete.

Effect of Low Temperatures on Fresh Concrete. Concrete subjected to low temperatures during placing, or within a few hours after being placed,

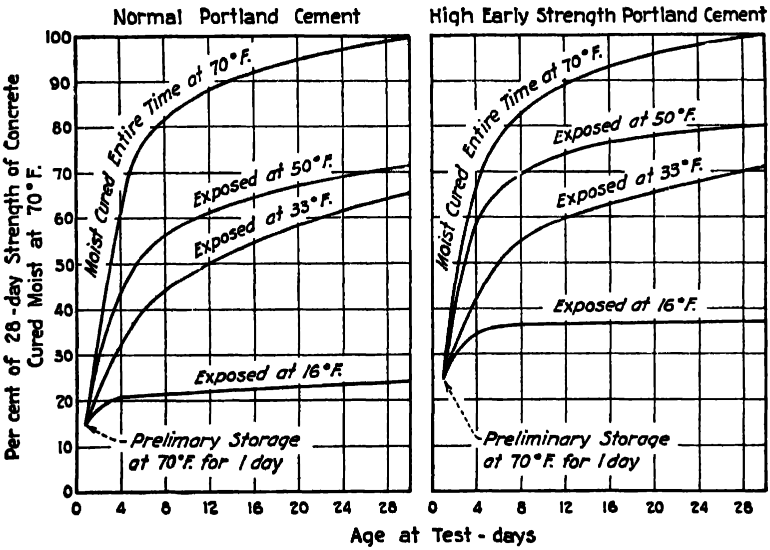


FIG. 92. Influence of temperature on compressive strength of concrete at different ages. Four- by eight-in. concrete cylinders. Mix 1-2.78-3.33 by weight for normal cement and 1-2.52-3.03 by weight for high early-strength cement; net water content 6 gal. per sack of cement. Specimens soaked 1 to 3 hr. before testing.

is greatly reduced in strength if maintained constantly at such temperatures. At low temperatures the hydration of the cement and its accompanying hardening are retarded. If freezing of the fresh concrete takes place, the strength may be permanently impaired. Most damage is caused by the formation of minute ice crystals which destroy the bond between the cement paste and the aggregate particles and disrupt the mass.

In Fig. 92 are shown relations between the relative compressive strength of concrete and age of test for temperatures ranging from 16 to 70°F. The diagrams for both normal (A.S.T.M., type 1) and high-early-strength cement (A.S.T.M., type 3) show the marked reduction in strength which occurs at all ages when concrete is cured at temperatures below 70°F.

Thus, in order to secure the same strength as would be obtained from concrete of a given water ratio cured at 70°F. for a given period, it is necessary either to prolong the curing period or reduce the water-cement ratio. Reducing the water-cement ratio requires more cement to produce concrete of a given consistency and hence increases the cost.

If it is necessary to place concrete when the temperature of the surrounding air is below 40°F., the aggregates and mixing water should be heated so that the temperature of the concrete when placed will be between 70 and 80°F. The concrete should be protected with canvas or other suitable coverings as soon as it is placed.

Structures erected during cold weather should be enclosed with tarpaulins or by other means and the enclosed spaces heated with steampipes, salamanders, or oil burners. It is desirable to maintain a temperature of not less than 70°F. for 3 days, or 50°F. for 5 days. However, when high-early-strength concrete is used, the temperature should be maintained at not less than 70°F. for 2 days, or 50°F. for 3 days, or for as much longer time as is necessary to ensure proper curing of the concrete. During such heating the concrete should be kept moist in order to offset the drying effect of the heated atmosphere.

Calcium chloride is sometimes added to the mixing water to accelerate the hardening of concrete and thus shorten the period of protection from low temperatures. Such additions should not be relied upon to lower the freezing point of the concrete since the optimum quantity for acceleration (approximately 2 to 3 per cent by weight of the cement) is too small to lower the freezing point of the mixing water more than a few degrees. The use of sodium chloride (common salt) to prevent freezing is not to be recommended in any case since it has been found to reduce the strength of the concrete even when used in relatively small amounts.

Forms and Molds for Concrete. In the usual concrete construction, forms, generally of wood or steel, are set up in place for a portion of the structure, and the freshly mixed concrete is deposited in these forms. After the concrete has attained sufficient strength, the forms are removed. Frequently they can be reused a number of times in the same structure.

On large concrete jobs, standardized panel forms of wood or steel are commonly used. This makes possible more rapid erection and removal. For large, plain surfaces, wooden forms are sometimes faced with large sheets of plywood or fiber board to eliminate the marking caused by joints between boards. In some cases the forms are provided with absorbent linings to eliminate air bubbles, remove excess water, and thereby produce a uniformly textured surface of high weather resistance. Exposed concrete exteriors of buildings and monumental structures frequently involve intricate ornamentation which must be cast in place.

This is usually accomplished by means of plaster waste molds which are built into place with the forms.

Whatever the type of forms used, they should be securely braced to prevent bulging or shifting under the hydrostatic pressure of the fresh concrete. Joints should be made as tight as possible to prevent leakage of cement paste and consequent sand seams and honeycomb on the concrete surface. Form surfaces are usually oiled or lacquered to facilitate removal from the hardened concrete.

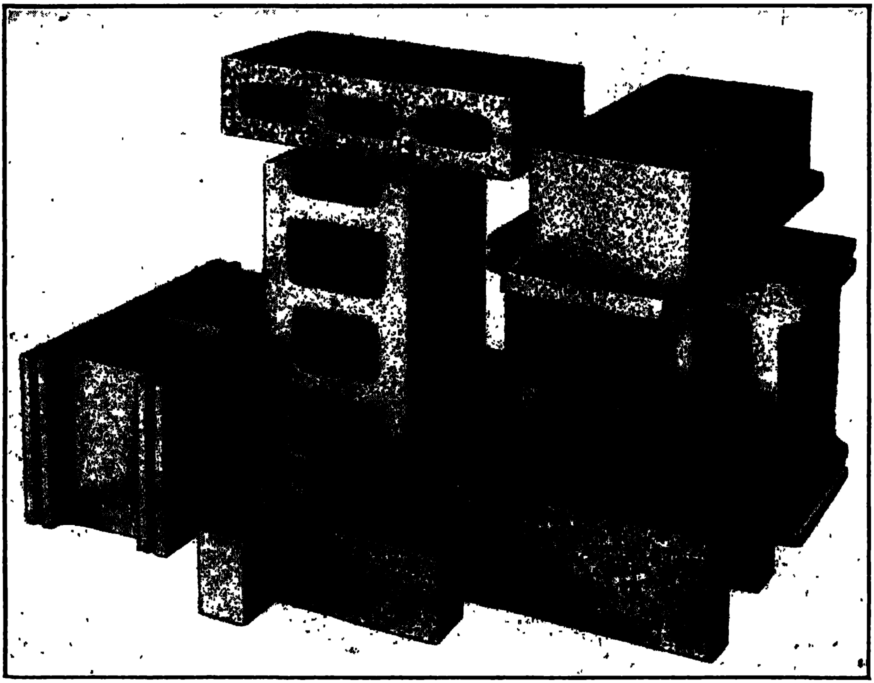


FIG. 93. Typical concrete masonry units. (*Courtesy of Besser Manufacturing Co., Alpena, Mich.*)

The period during which the forms must be left in place may be as little as 24 hr. for vertical faces. Supporting forms or shoring under slabs, beams, and other horizontal members must remain in place until the concrete can support its own weight together with such live loads as may be imposed during construction. This usually requires from 7 to 10 days. In cold weather, when hardening of concrete is retarded by low temperatures, these periods must be extended. Premature removal of forms may result in the collapse of a portion of the structure. In removing forms, care must be taken to avoid injury to the partially hardened concrete, particularly at the edges and corners.

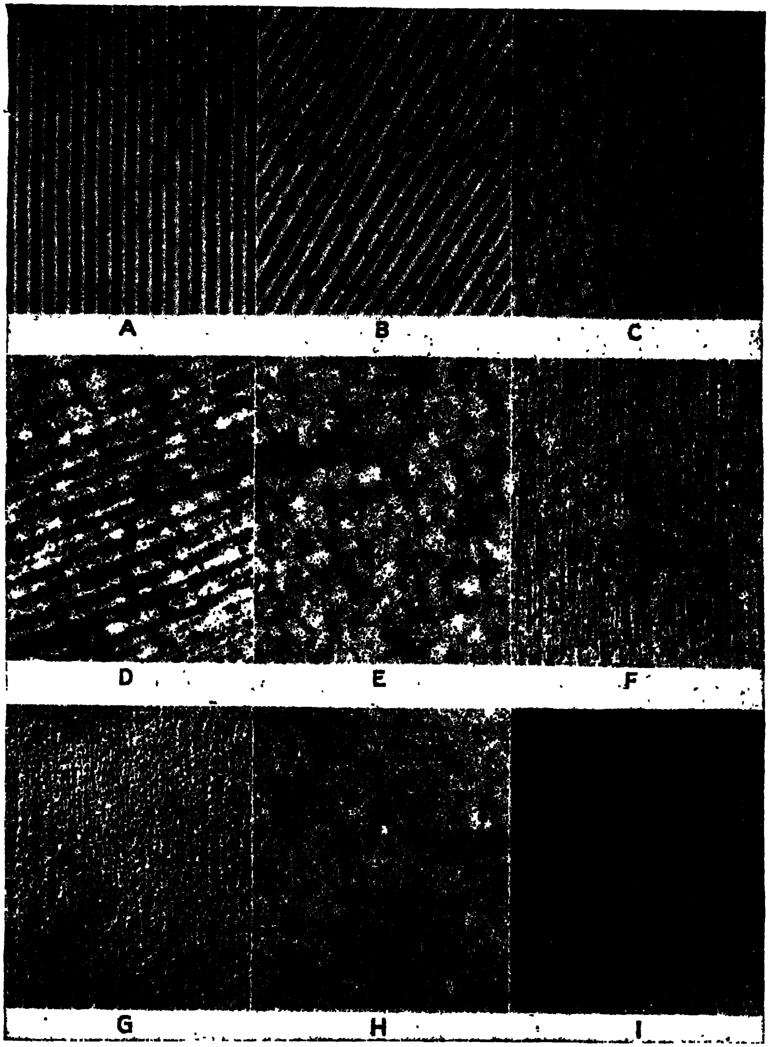


FIG. 94. Concrete building stone surface finishes. *A*, machine-tooled finish; *B*, hand-tooled finish; *C*, crandalled finish; *D*, sawed finish; *E*, planer-rubbed finish; *F*, bush-hammered finish; *G*, combed finish; *H*, hand-rubbed finish; *I*, brushed finish.

The units which make up a concrete structure—beams, columns, and other structural members—are sometimes cast separately and afterward fitted together to form the structure. This is the *unit* system of casting. With this system it is frequently feasible to use metal forms and by their use to produce members of fine surface finish which are very uniform in size. In structures made up of separately cast units the strength of the joints between members must be carefully considered.

Concrete art tile, blocks for masonry walls, drain tile, and sewer pipe are made in metal molds. Such units are frequently made of very dry concrete (Fig. 93) which, by thorough tamping or great pressure, is given sufficient rigidity so that it can be removed from the molds immediately. The molded units are then exposed to moist steam or to water-saturated air until they have gained sufficient strength to be transferred to a storage

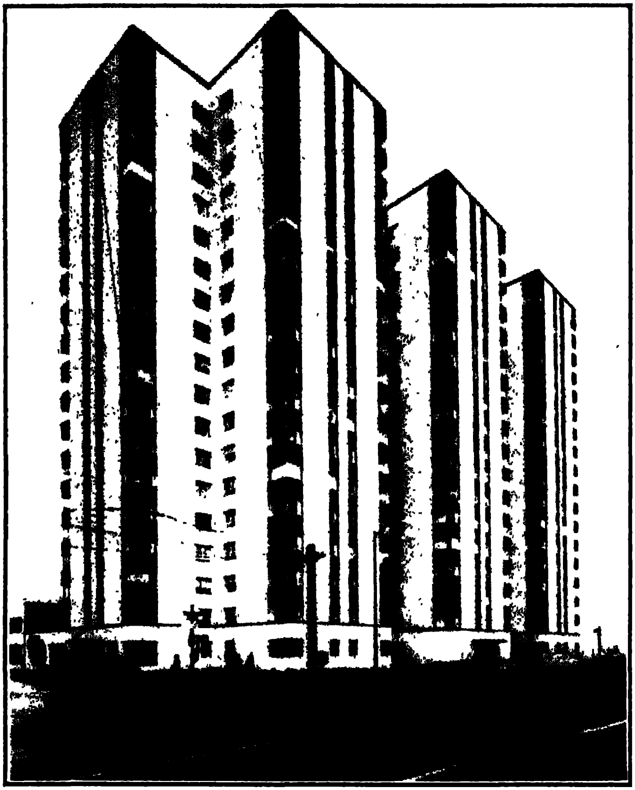


FIG. 95. Architectural-concrete building.

yard for further curing. Concrete blocks are usually made hollow and are of a great variety of shapes and sizes (Fig. 93).

Concrete building stone is produced in metal, sand, wood, or plaster molds. It is usually tooled or otherwise surface treated to expose the special aggregates of which it is composed. Many beautiful stones not available in conventional block form for architectural work because of their scarcity or the high cost of fabrication can be crushed and used as aggregate in concrete stone and thus be made available for building purposes. Figure 94 shows some of the finishes which may be obtained in concrete stone.

A wide variety of architectural effects is possible by exposing the exterior surfaces of the concrete forming the walls of reinforced concrete buildings so as to show the form marks, by using various types of form material, or by exposing the aggregates. Sometimes the exposed surfaces are painted (Fig. 95) or treated with portland-cement stucco in order to bring out desired effects.

STRENGTH OF CONCRETE

The strength and other properties of concrete made from sound materials are largely determined by the quality of the cement-water paste which

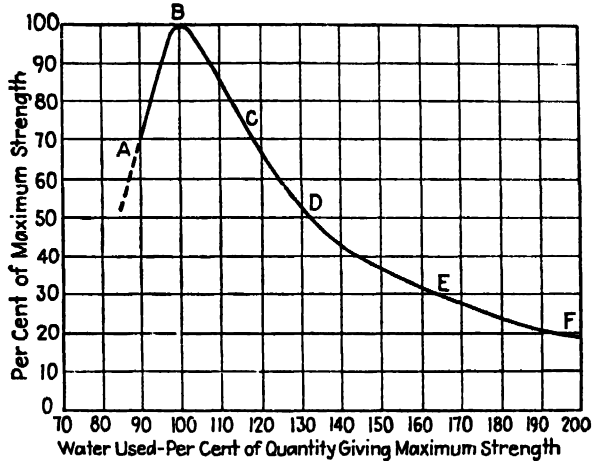


FIG. 96. Effect of quantity of mixing water on strength of concrete. (*Courtesy of D. A. Abrams.*)

in turn is dependent on (1) the characteristics of the cement, (2) the proportion of water to cement—the water-cement ratio, and (3) the extent to which the water has combined with the cement, as governed by the conditions and duration of the curing.

In general the commonly used portland cements, when tested in concrete under controlled conditions, behave similarly and tend eventually to attain approximately the same strength. Therefore, the difference between such cements, as far as concrete strength is concerned, is largely a matter of the rate of gain in strength at different ages rather than of potential strength.

The marked influence of water-cement ratio and curing has been pointed out previously, but, since these two factors are of such great importance, their effect on strength and other properties of concrete cannot be too strongly emphasized.

The curve in Fig. 96, plotted from the results of tests made by D. A.

Abrams, shows the general relation between strength of concrete and the amount of mixing water for given proportions of cement to aggregate. This is a composite curve which summarizes the results of compression tests on a wide range of mixtures of cement and aggregate, the grading of the mixed aggregate being the same in all cases but the concrete varying in consistency from very dry to very wet. It will be noted that the strength increases rapidly with increase in the quantity of mixing water over the limited range on the curve indicated by *AB*. With further increase in the amount of water the strength falls off rapidly as indicated by the portion of the curve *BCDEF*. Concretes made with the quantity of water represented by the range *AB* are too dry and stiff for most purposes but could be used in making masonry units, drain tile, and other concrete products requiring a dry mixture, or in mass work when compacted by high-frequency vibrators or tamping. The range of plastic consistencies in which the concretes are not too dry for placing by the usual methods nor so wet as to segregate extends from about 110 to 150 per cent of the quantity of water giving maximum strength. The proper amount of water for concrete used in road construction corresponds to that at *C*. The amount of water used in building construction frequently corresponds to that portion of the curve from *D* to *F* and it is evident that only about 30 per cent of the potential strength is obtained with such wet mixtures.

Tensile, Flexural, and Compressive Strength. Curves showing relations between the water-cement ratio and the tensile, flexural, and compressive strengths of moist-cured concrete for several different mixtures, consistencies, and ages at test are given in Fig. 97. It will be noted that the curves for the three types of test at the different ages are not only similar to each other but also resemble the curve in Fig. 82, and that in Fig. 96 over the range *BCDEF*. The data on which these curves are based clearly demonstrate that for plastic, workable mixtures the water-cement ratio is a governing factor in the strength of concrete, whether it is tested in tension, flexure, or compression. Increase in the water-cement ratio causes a reduction in strength in all three types of test.

Table XXXI, based on the same data from which Fig. 97 was plotted, gives a direct comparison of the compression, flexural, and tensile strength of concrete. The data in this table show that for concretes of from 2,000 to 6,000 lb. per sq. in. compressive strength, the modulus of rupture ranged from about 20 to about 12 per cent of the compressive strength, while the tensile strength ranged from about 10 to 8 per cent of the compressive strength and from about 50 to 60 per cent of the modulus of rupture. Flexural strength is of particular importance in the design of

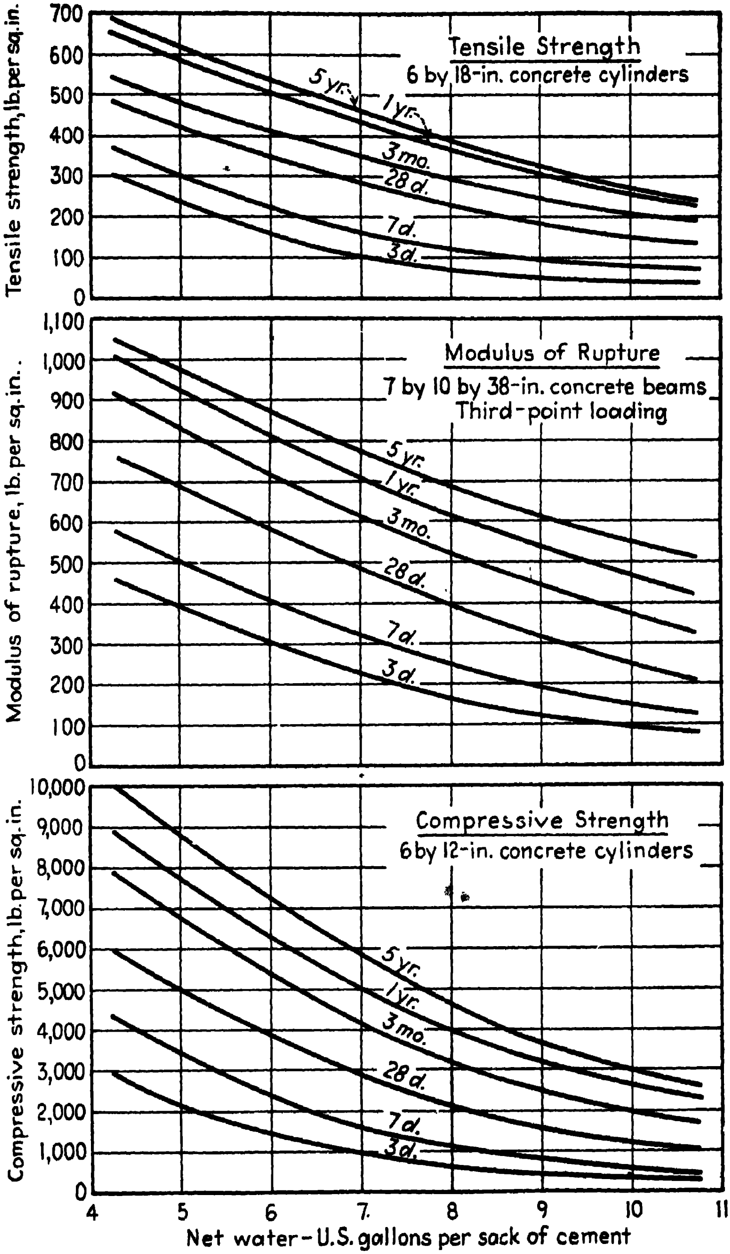


FIG. 97. Compressive, flexural, and tensile strength of concrete of varying water content at different ages.

TABLE XXXI. COMPARISON OF COMPRESSIVE, FLEXURAL, AND TENSILE STRENGTH OF PLAIN CONCRETE

Strength of plain concrete, lb. per sq. in.			Ratio, per cent		
Compressive	Modulus of rupture	Tensile	Modulus of rupture to compressive strength	Tensile strength to compressive strength	Tensile strength to modulus of rupture
1,000	230	110	23.0	11.0	48
2,000	375	200	18.8	10.0	53
3,000	485	275	16.2	9.2	57
4,000	580	340	14.5	8.5	59
5,000	675	400	13.5	8.0	59
6,000	765	460	12.8	7.7	60
7,000	855	520	12.2	7.4	61
8,000	930	580	11.6	7.2	62
9,000	1,010	630	11.2	7.0	63

concrete roads. Tensile strength, except in special cases, is not considered in the design of reinforced-concrete structures.

Effect of Age on Strength. That well-made concrete when cured at favorable temperatures in the presence of moisture gains strength with passage of time is brought out by the age-strength curves in Fig. 98, which are based on the same data used in plotting Fig. 97. A constant consistency giving a slump of about 4 in. was used with each of the mixes represented in Fig. 98. For each type of test the strengths increased with age, but at a diminishing rate. These tests were made under laboratory conditions, and the specimens were cured in moist air at a temperature of 70°F. The strengths at 1 year were from about 1.3 to 1.8 times those at 28 days, depending on the mix and type of test. Under conditions of use where concrete receives no additional moisture after placing, little gain in strength can be expected after the uncombined mixing water has evaporated.

High-early-strength Concrete. It is sometimes desirable to produce concrete having comparatively high strength within a few days after placing in order to put it into use as early as possible. It is particularly advantageous to develop high early strength in concrete used for pavement repairs, pavement intersections, high-speed building construction, and cold-weather work.

High-early-strength concretes can be made either from normal portland

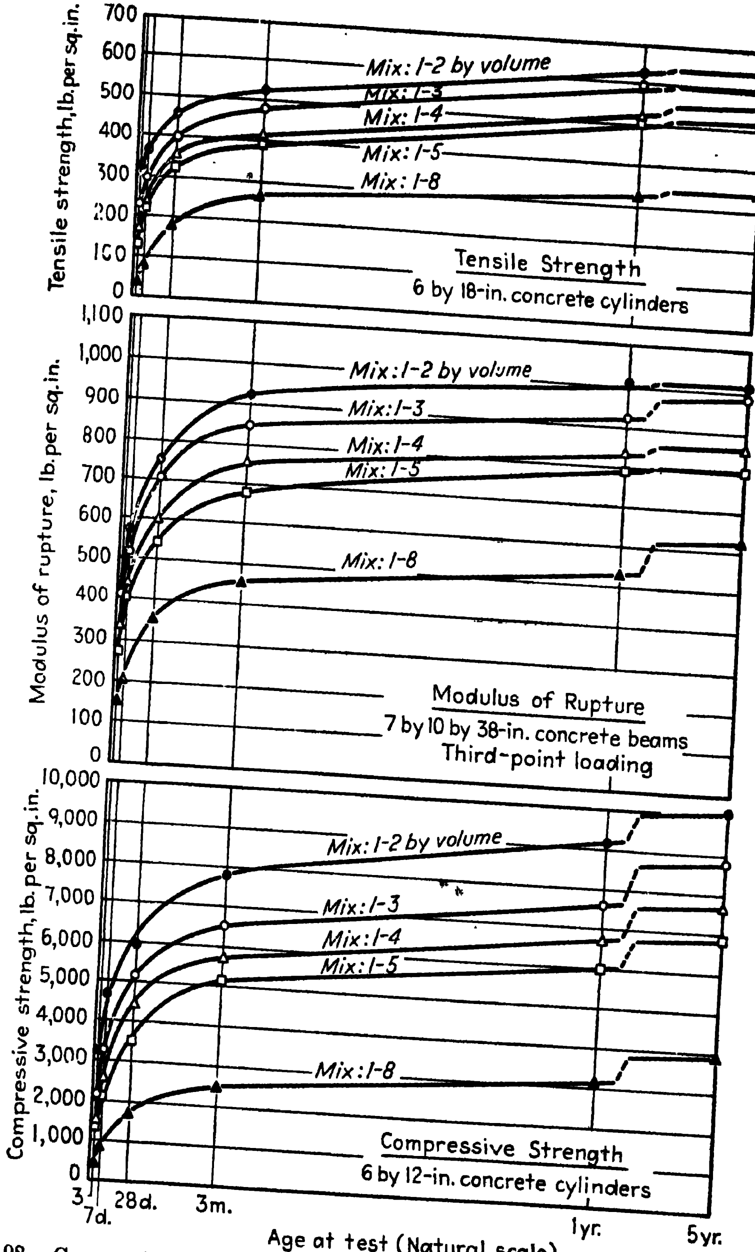


FIG. 98. Compressive, flexural, and tensile strength of various concrete mixes at different ages.

cements or from special high-early-strength cements. High-early-strength cements possess advantages where high quality at periods of 1 or 2 days is essential or where extended curing cannot be had. Ordinarily, considerations of convenience and economy will determine which type of cement to use. If normal portland cement is used, the quantity must be greater and the water-cement ratio lower than that required to produce the same strength at a later age.

Referring to the diagram at the left in Fig. 99 it will be seen that concrete with 3,000 lb. per sq. in. compressive strength at 28 days could be obtained with normal portland cement (A.S.T.M., type 1) by using a

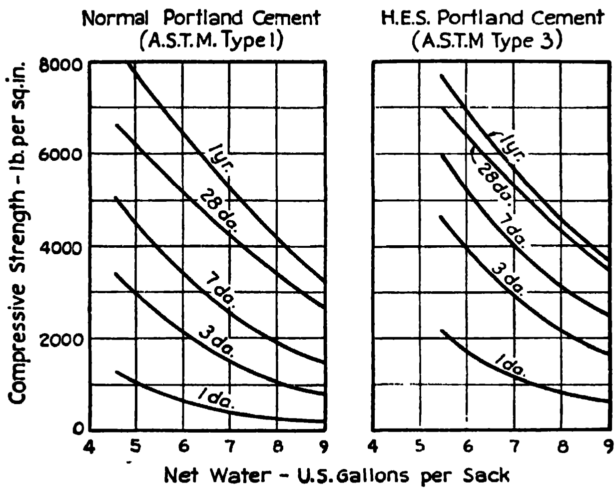


FIG. 99. Water-cement ratio-strength relations for concrete made with normal and with high early-strength cements.

water-cement ratio of 8½ gal. per sack, and that in order to obtain this strength in 3 days, the water ratio must be reduced to 5 gal. per sack. With high-early-strength cement (A.S.T.M., type 3) the water ratio required to produce a compressive strength of 3,000 lb. per sq. in. in 3 days will, according to the right-hand diagram in Fig. 99, be 7 gal. per sack, which is the same as that required to produce this strength at about 10 days using normal portland cement.

An admixture of calcium chloride, dissolved in the mixing water, is sometimes employed to accelerate the hardening and increase the strength at early ages.

Shearing Strength. Table XXXII gives the average results of a large number of tests made at the University of Illinois on the strength of concrete in direct shear. The average apparent strength in shear is slightly greater than one-half of the compressive strength for rich con-

crete and a somewhat greater proportion of the compressive strength of lean concrete. Probably the failures in these shear tests were really

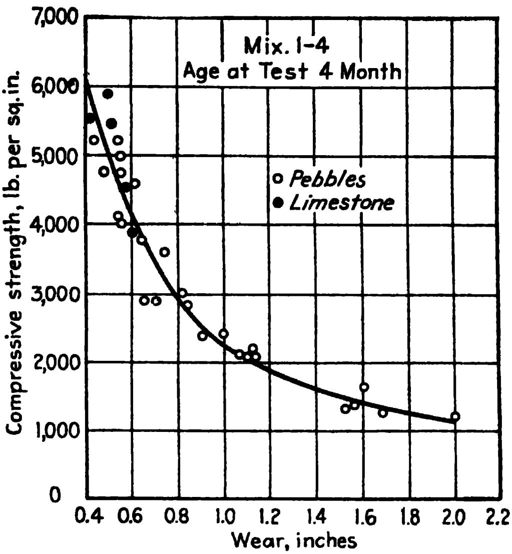


FIG. 100. Relation between compressive strength and wear of concrete. (*Courtesy of D. A. Abrams.*)

more nearly tension failures starting on inclined planes than shear failures.

Wear Resistance. Figure 100 shows the relation between compressive strength and wear of a 1-4 concrete mixture such as is commonly used in concrete roads and pavements. The concrete in these tests was of

TABLE XXXII. STRENGTH OF PORTLAND-CEMENT CONCRETE UNDER SHEAR

The values given below summarize test results shown in *Bulletin* 8 of the Engineering Experiment Station of the University of Illinois. All concrete was made and stored under laboratory conditions and tested when 60 days old. The aggregate used was torpedo-bank sand and soft limestone.

Proportion of cement to aggregate	Ultimate strength, lb. per sq. in.		Ratio of strength in shear to strength in compression
	Shear	Compression	
1-6 *	1,290	2,430	0.53
1-9 *	1,090	1,290	0.84

* Total volume fine and coarse aggregates measured separately.

different consistencies and was cured under different conditions. The amount of wear was determined by testing blocks of concrete in a Talbot-Jones rattler with an abrasive charge of cast-iron balls. It will be noted that the amount of wear decreased rapidly with increase in compressive strength.

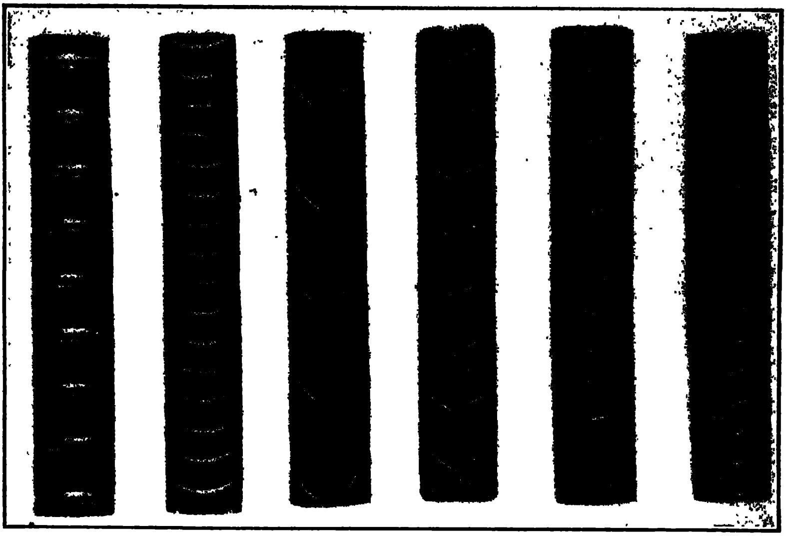
Bond Strength. The strength of the bond between the concrete and the steel reinforcement is of great importance in reinforced concrete, since lack of bond prevents the two materials from working together as intended and thus seriously impairs the load-carrying capacity of reinforced structural members.

In the early days of reinforced-concrete construction, plain steel bars were generally employed as reinforcement, whereas today most steel reinforcement consists of so-called *deformed* bars like those shown in Fig. 101(*a*). Deformed bars have projections on the surface for the purpose of giving the bars a positive mechanical anchorage in the concrete. The effectiveness of such anchorage lies in its holding power after some slip has taken place, rather than in any tendency to prevent slip altogether.

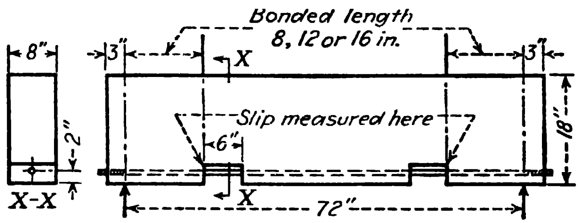
The diagrams in Fig. 101(*c*) compare the average bond resistance of ⅞-in. deformed and plain round bars when tested with different lengths of embedment in beams made with concrete having a compressive strength of 3,500 lb. per sq. in. at 28 days. The deformed bars, all of which met the requirements of A.S.T.M. Specification A305, "Minimum Requirements for the Deformations of Deformed Steel Bars for Concrete Reinforcement," developed much higher bond stresses than the plain bar at a given slip of bar. At a slip of 0.010 in., the average bond stress developed by the deformed bars was about three times that developed by the plain bar.

Figure 101(*a*) shows deformed bars commercially available which comply with A.S.T.M. Specification A305. With such deformed bars, higher unit bond stresses are allowed (see Table XXXIII), the length of embedment required to provide adequate end anchorage of bars is reduced, the tendency toward formation of tension cracks and the width of crack is reduced, and there is greater interaction between the concrete and steel than with plain bars. The high bond resistance developed by the deformed bars makes them well suited not only for the usual reinforced-concrete construction but also for assemblies in which the reinforcing steel is prestressed.

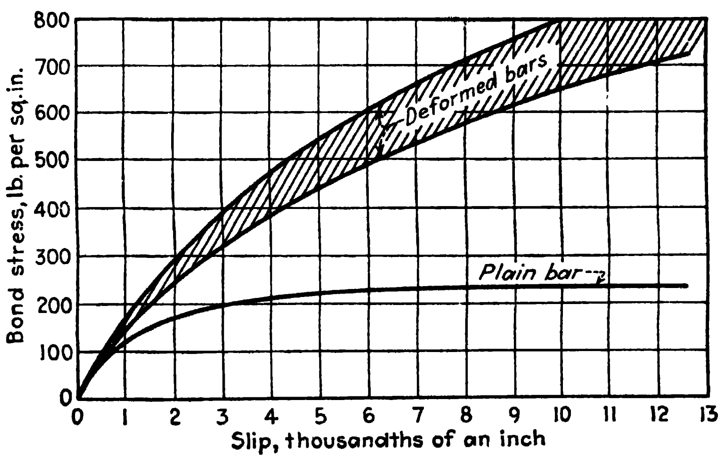
Working Stresses in Concrete. The allowable working stresses in concrete recommended in the "Building Code Requirements for Reinforced Concrete" (ACI 318) of the American Concrete Institute are given in Table XXXIII. In this table, f' equals the minimum specified compressive strength at 28 days or at the earliest age at which the concrete may be expected to receive its full load.



(*a*) Typical deformed reinforcing bars meeting A.S.T.M. minimum requirements for deformations of deformed steel bars for concrete reinforcement.



(*b*) Type of beam used for determining slip of reinforcing bars.



(*c*) Average bond-slip curves for ⅞-in. deformed and plain round bars embedded in concrete beams. Slip of bars measured at loaded end as shown in (*b*).

FIG. 101. Deformed reinforcing bars and bond resistance of plain and deformed round bars.

TABLE XXXIII. ALLOWABLE UNIT STRESS IN CONCRETE

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In this table, f' equals the specified compressive strength at 28 days or at the earliest age at which the concrete may be expected to receive its full load.

Description		Allowable unit stresses: For any strength of concrete $n = \frac{30,000}{f_c'}$	Maximum value, psi	For strength of concrete shown below: $f_c' =$ 2000 psi $n = 15$	$f_c' =$ 2500 psi $n = 12$	$f_c' =$ 3000 psi $n = 10$	$f_c' =$ 3750 psi $n = 8$
Flexure: f_c							
Extreme fiber stress in compression	f_c	$0.45f_c'$		900	1125	1350	1688
Extreme fiber stress in tension in plain concrete footings	f_c	$0.03f_c'$		60	75	90	113
Shear: v (as a measure of diagonal tension)							
Beams with no web reinforcement	v_c	$0.03f_c'$		60	75	90	113
Beams with properly designed web reinforcement	v	$0.12f_c'$		240	300	360	450
Flat slabs at distance d from edge of column capital or drop panel	v_c	$0.03f_c'$		60	75	90	113
Footings	v_c	$0.03f_c'$	75	60	75	75	75
Bond: u							
Deformed bars							
Top bars*	u	$0.07f_c'$	245	140	175	210	245
In 2-way footings (except top bars)	u	$0.08f_c'$	280	160	200	240	280
All others	u	$0.10f_c'$	350	200	250	300	350
Plain bars (must be hooked)							
Top bars	u	$0.03f_c'$	105	60	75	90	105
In 2-way footings (except top bars)	u	$0.036f_c'$	126	72	90	108	126
All others	u	$0.045f_c'$	158	90	113	135	158
Bearing: f_c							
On full area	f_c	$0.25f_c'$		500	625	750	938
On one-third area or less†	f_c	$0.375f_c'$		750	938	1125	1405

* Top bars are horizontal bars so placed that more than 12 in. of concrete is cast in the member below the bar.

† The allowable bearing stress on an area greater than one-third but less than the full area shall be interpolated between the values given.

Except for bond, these allowable working stresses conform in general with those given in the report of the Joint Committee on Standard Specifications for Concrete and Reinforced Concrete. The allowable bond unit stresses for deformed bars apply to bars with deformations conforming to A.S.T.M. Specification A305, "Minimum Requirements for the Deformations of Deformed Steel Bars for Concrete Reinforcement."

Modulus of Elasticity of Concrete. Knowledge of the modulus of elasticity of concrete is essential in designing reinforced-concrete members and structures. Comprehensive data on modulus of elasticity are reported by Stanton Walker in a paper, "Modulus of Elasticity of Concrete," published in the 1919 *Proceedings* of the A.S.T.M., in which it was shown that the factors which affect compressive strength of concrete have a similar effect on modulus of elasticity. Walker found no marked difference either in the modulus of elasticity or in the compressive strength of concrete made from high-grade gravel, crushed limestone, crushed granite, or blast-furnace slag. The secant modulus of elasticity,[1] and sometimes the initial tangent modulus of elasticity, are used in design calculations. Values of the initial tangent modulus of elasticity for both tension and compression tests of concrete are given in Table XXXIV. In these tests the secant modulus was virtually the same as the initial tangent modulus for loads up to about one-third the ultimate strength of the concrete. From Table XXXIV, it is seen that increasing the richness of the mix (decrease in water-cement ratio) caused an increase in both modulus of elasticity and strength; also that both modulus of elasticity and strength increased with age. An interesting feature of these data is that the values of the initial tangent modulus are about the same for tension as for compression.

Fatigue or Endurance Limit for Repeated Stress. Plain concrete will fail under repeated applications of a stress varying from zero to a maximum which exceeds about 50 to 60 per cent of its ultimate strength. Since the strength properties of concrete will vary, depending upon the age, moisture condition, and other characteristics, repeated load tests on concrete must be conducted at ages and under conditions that will not cause a change in the concrete during the period of test. According to W. K. Hatt the endurance limit of concrete is influenced by the rapidity of application of load and the period of rest between a series of loadings, the

[1] The secant modulus of elasticity is measured by the slope of the chord to the stress-strain diagram at any given stress. The tangent modulus is measured by the slope of the tangent to the stress-strain diagram at any given stress. The initial tangent modulus is measured by the slope of the tangent to the stress-strain diagram near its beginning.

latter factor being more important in the case of a material like concrete than in the case of steel, where it is negligible at room temperature.

Rapidly repeated load tests of concrete in compression by J. L. Van Ornum showed an endurance limit of about 50 per cent of the ultimate strength as determined in the usual progressive or static load test. That is, when the applied stress is lower than about 50 per cent of the ultimate

TABLE XXXIV. COMPRESSIVE AND TENSILE STRENGTH AND MODULUS OF ELASTICITY OF CONCRETE

Compression tests of 6- by 12-in. and tension tests of 6- by 18-in. concrete cylinders.

Aggregate: Elgin sand and gravel graded 0- to 1½-in.; aggregate grading and consistency constant.

Specimens removed from molds after 1 day and cured in moist room at 70°F. until test, tested damp.

Deformation of concrete measured with a Martens mirror extensometer.

Mix by volume	Cement sacks per cu. yd.	Net water-cement ratio	Strength, lb. per sq. in.						Initial tangent modulus of elasticity, 1,000 lb. per sq. in.					
			3 da.	7 da.	28 da.	3 mo.	1 yr.	5 yr.	3 da.	7 da.	28 da.	3 mo.	1 yr.	5 yr.
							Compression							
1-2	10.5	0.57	3,220	4,650	5,960	7,810	9,170	10,160	2,870	3,340	3,770	4,460	5,530	5,750
1-3	7.8	0.64	2,160	3,250	5,140	6,500	7,570	8,820	2,490	2,930	3,480	4,200	5,400	5,650
1-4	6.3	0.76	1,560	2,620	4,460	5,710	6,720	7,750	2,310	2,660	3,340	3,740	5,340	5,580
1-5	5.2	0.85	1,340	2,120	3,510	5,130	6,010	6,860	2,230	2,590	3,130	3,610	5,340	5,570
1-8	3.4	1.13	480	945	1,740	2,550	3,140	3,930	1,710	1,990	2,770	3,420	4,970	5,530
							Tension							
1-2	10.5	0.57	325	360	460	525	630	635	2,770	3,200	4,050	4,450	5,500	5,550
1-3	7.8	0.64	230	290	400	480	595	590	2,770	3,130	3,840	4,050	5,250	5,600
1-4	6.3	0.76	175	240	360	415	525	565	2,700	3,000	3,560	4,150	5,470	5,380
1-5	5.2	0.85	130	225	325	390	510	520	2,420	2,780	3,200	3,630	5,160	5,300
1-8	3.4	1.13	40	85	185	270	335	350	2,210	2,700	3,030	3,410	4,840	4,700

compressive strength, a practically unlimited number of repetitions of that stress can be applied without failure.

Tests reported by E. Probst also indicate that the endurance limit of plain concrete in compression is about 47 to 60 per cent of the ultimate static strength.

In tests of concrete and mortar beams by the Illinois Highway Department it was found that a flexural stress of 50 per cent of the ultimate strength under progressive loading could be repeated an indefinite number of times without failure. A stress of 60 per cent of the ultimate caused failure after about 30,000 repetitions while a stress of 70 per cent caused

failure after about 5,000 repetitions. In these tests the number of applications of load was 40 per minute and there was no period of rest during the test. Accelerated failure was also noted in an experimental concrete test road when the stress exceeded 50 per cent of the modulus of rupture of the concrete.

Tests at Purdue University of dry 1–2 mortar beams over 6 months old showed that the endurance limit under alternating tension and compression loads was about 54 per cent of the progressive breaking load. The number of reversals of stress necessary to cause failure decreased in proportion to the increase in the percentage of stress above the endurance limit. A marked recovery in deformation and stiffness during rest periods was observed in these tests. The endurance limit for a saturated mortar was found to be lower than for a dry mortar.

Watertightness. It is not difficult to secure watertight concrete with portland cement without the use of special materials, if attention is paid to the control of the factors which influence watertightness.

The same factors which influence strength and other properties of concrete also greatly affect watertightness. In order to produce watertight concrete it is essential that sound aggregates of low porosity be incorporated in an impervious cement-water paste. To secure an impervious paste a relatively low water-cement ratio must be used and the concrete must be sufficiently cured, since watertightness of the paste is greatly influenced by the extent to which the chemical reactions have progressed before it is subjected to water pressure and this in turn is controlled by the kind and duration of the curing.

Permeability Tests. The marked influence of the water-cement ratio and the duration of curing on the watertightness of 6- by 1-in. mortar disks are shown in Fig. 102. In these tests three different water-cement ratios were used, the specimens being subjected to a water pressure of 20 lb. per sq. in. for 48 hr. after different periods of moist curing at 70°F. The water actually passing through the disks was caught and measured by means of the apparatus illustrated in the upper right-hand corner of Fig. 102.

The diagrams in Fig. 102 show in a striking manner how greatly the leakage at a given age is reduced by a reduction in the water-cement ratio. They also show that for a given water ratio the leakage rapidly decreases with duration of moist curing until it finally ceases entirely. These results emphasize how important it is, where watertightness is desired, to extend the curing period until the internal structure of the paste is built up to the point where it is impervious to water.

In addition to the factors just discussed it is also essential that plastic, workable mixes be used so that they may be easily placed without segrega-

tion and also that the concrete be thoroughly mixed. Where possible, placing should be continuous and care taken to avoid undue accumulation of water on the surfaces of the layers. It is essential that cracking of the concrete due to settlement, or to shrinkage in setting and to temperature changes, be avoided in watertight construction. Consequently, reinforcing steel and expansion joints must generally be provided to aid in preventing the formation or extension of cracks. Where settlement or

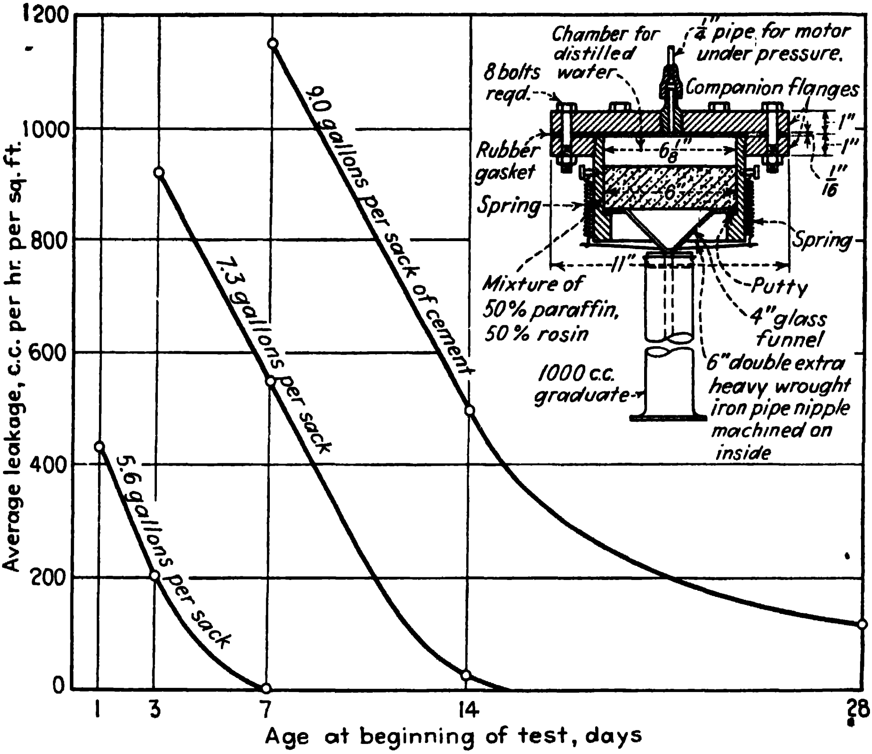


FIG. 102. Apparatus for measuring permeability, and effect of water content and curing on permeability of concrete.

contraction cracks are likely to occur, the use of a flexible membrane consisting of a heavy bituminous application, alternate layers of tar and burlap or tarred felt, may be necessary.

Waterproofing. Various waterproofing compounds to be mixed with concrete materials, powdered admixtures, and waterproofing coatings are on the market. These are not necessary to obtain watertight concrete if proper attention is given to the selection of aggregates and to the proportioning, placing, and curing of the concrete. Waterproof coatings, if applied as soon as the forms are removed, may be of some value for curing

by preventing evaporation of the uncombined water. The addition of finely divided powdered admixtures to a concrete mix generally necessitates the use of additional mixing water in order to maintain a given workability. Where this additional water is relatively large in amount a reduction in strength occurs, and little benefit in the way of watertightness can be expected. Tests of the permeability of concrete containing certain of the liquid and powdered admixtures now on the market have shown that the changes in watertightness brought about by their use are insignificant compared with the marked effects produced by an increased period of moist curing or small reductions in the water-cement ratio.

Durability of Concrete. A most important property of concrete which is to be subjected to severe conditions of exposure is durability. Experience has shown that the freezing of absorbed moisture is by far the most severe of the destructive agents usually encountered. Hence, an essential requirement for a durable concrete under severe exposures is watertightness. Watertight concrete prevents the ingress of water which upon freezing expands and tends to disrupt the concrete. Moreover, with watertight concrete there is no danger from percolating waters which might cause a slow breaking down of the concrete through solution of essential ingredients. Methods of obtaining watertight concrete were pointed out in the preceding section.

Durable aggregates are necessary in order to obtain watertight and durable concrete. Fortunately, the majority of aggregates used for concrete are of such mineral composition that they satisfactorily resist weathering.

While there is no test by which the durability of concrete can be directly measured, alternate freezing and thawing tests are frequently employed for this purpose and are regarded as affording the best indication of the probable durability of a concrete mixture. The effects of alternations of freezing and thawing are determined by various measurements such as the expansion, loss in weight, loss in strength, or reduction in *dynamic* modulus of elasticity of the concrete specimens during the test.

The effect of alternate freezing and thawing on 6-in. concrete cubes of three different water contents is illustrated in Fig. 103. These specimens were cured moist for 14 days and then stored in air for 14 days before freezing. The figure shows their condition after 100 alternations or cycles of freezing and thawing. The specimens made with 5½ gal. of water per sack of cement were only slightly scaled after 100 cycles, those made with 7 gal. of water showed appreciable scaling, while the specimens containing 9 gal. of water per sack of cement showed pronounced scaling of the surface caused by the expansive force of the water

freezing within the pores. These tests, and others covering a wide range in water-cement ratio, show how the resistance to freezing of concrete made with portland cement depends on the water content of the cement-water paste. Tests have shown that the duration of the period of moist cooling also has an important influence on durability.

Recommended water-cement ratios for different degrees of exposure are given in Table XXXIV. For a more detailed discussion of this subject, see reference 2 at the end of this chapter.

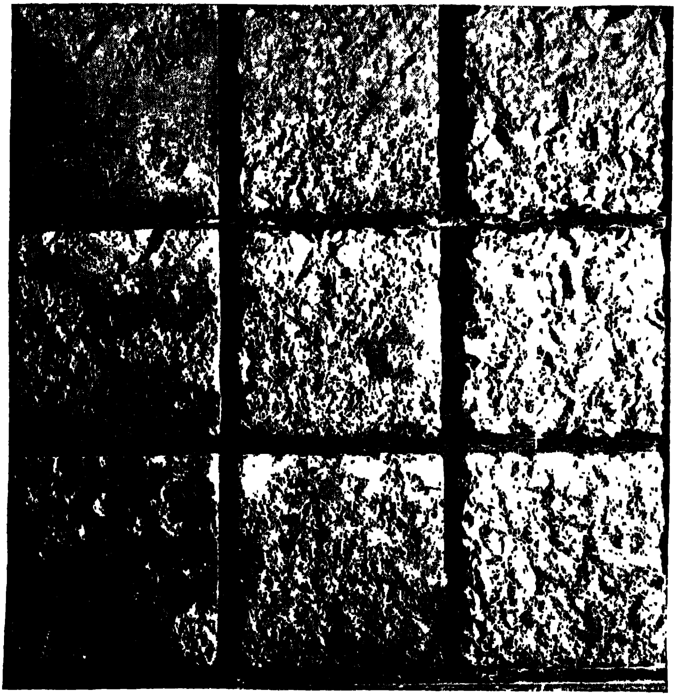


FIG. 103. Six- by six-inch concrete cubes after 100 cycles of freezing and thawing.

Air-entrained Concrete. Extensive laboratory and field tests have disclosed that the resistance of concrete to freezing and thawing, and to the surface scaling caused by the application of sodium chloride to concrete pavements to remove ice during the winter, can be very greatly improved by intergrinding very small quantities (0.01 to 0.05 per cent by weight of cement) of certain organic materials, such as natural resins and acid fats, with the cement or by adding them in suitable solutions at the mixer. These organic materials cause foaming during the mixing process and thereby produce minute, disconnected

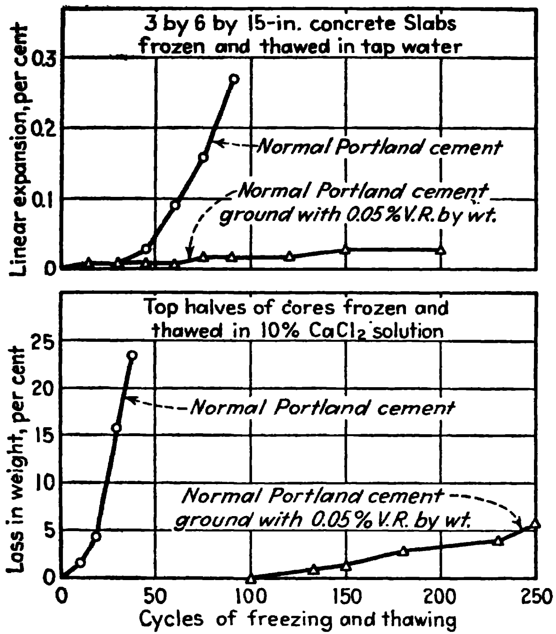
air voids in the concrete. These minute air voids increase the mobility, reduce the water requirement, and prevent segregation of the mix. The air thus introduced into the usual concrete mixes reduces the weight, strength, and other properties of the concrete somewhat but minimizes the ill effects of the freezing of water or salt solutions in the pores of the concrete.

In Fig. 104 are data of tests which show the very marked improvement in the resistance to freezing and thawing and to surface scaling of concrete specimens from a highway project which resulted from the use of a portland cement ground with 0.05 per cent of Vinsol resin by weight of the cement.

Figure 105 is based on freezing and thawing tests of concrete specimens made with a number of non-air-entraining portland cements which varied both in fineness and composition over a wide range. Some of the cements were used also with varying amounts of neutralized Vinsol resin (NVX) added in solution in the mixing water to obtain air-entrained concretes. The specimens were cured moist for 28 days and then soaked in water for 3 days prior to test and thus were particularly vulnerable to damage from the freezing of water in the pores when subjected to freezing and thawing test.

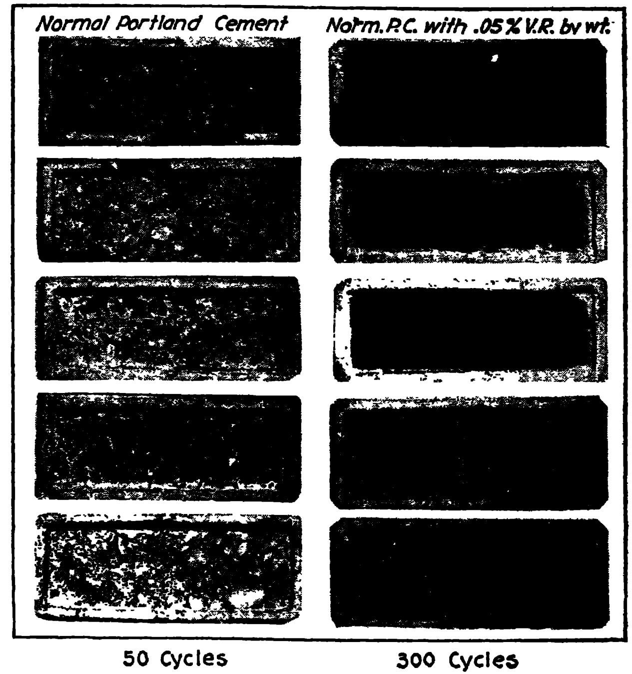
Although there were differences in the resistance to freezing and thawing of the non-air-entrained concretes (shown by solid circles in rectangle at lower left-hand corner of the figure), as determined by the number of cycles required to produce an expansion of 0.1 per cent, none could be considered as very frost resistant under the conditions of these tests. These had air contents of less than 1.3 per cent and had expanded 0.10 per cent in from 3 to 107 cycles of freezing and thawing, regardless of the composition or fineness of the cement. On the other hand, as the air content of the concrete was purposely increased by the use of the air-entraining addition, the resistance to freezing and thawing was markedly increased. The concretes having air contents of 4.4 and 5.7 per cent sustained 2,175 cycles of freezing and thawing without expanding 0.1 per cent, whereas the concretes made with the same cements but without the air-entraining addition expanded 0.1 per cent in less than 10 cycles. These results further demonstrate the beneficial effect of purposely entraining protective air, and that the air content of the concrete is of far more significance with regard to frost resistance than the fineness or composition of the cement.

A total air content of from 4 to 5 per cent by volume gives satisfactory improvement in durability without serious loss in strength, particularly if advantage is taken of the greater workability of the air-entrained concrete to reduce the sand and water content of the mixture. Experi-



(a)

Expansion of slabs and losses in weight of highway concrete-cores during freezing and thawing.



(b)

Views of tops of 3- by 6- by 15-in. concrete test slabs after 50 and 300 cycles of freezing and thawing. Flake calcium chloride applied to ice frozen on top surface.

FIG. 104. Tests of highway concrete made with portland cement ground with and without Vinsol resin.

ence has shown that from 3 to 6 per cent total air constitutes a reasonable working range for control purposes. A number of state highway departments have adopted these limits in their specifications for air-entrained concrete for pavements and bridges. These same limits are usually

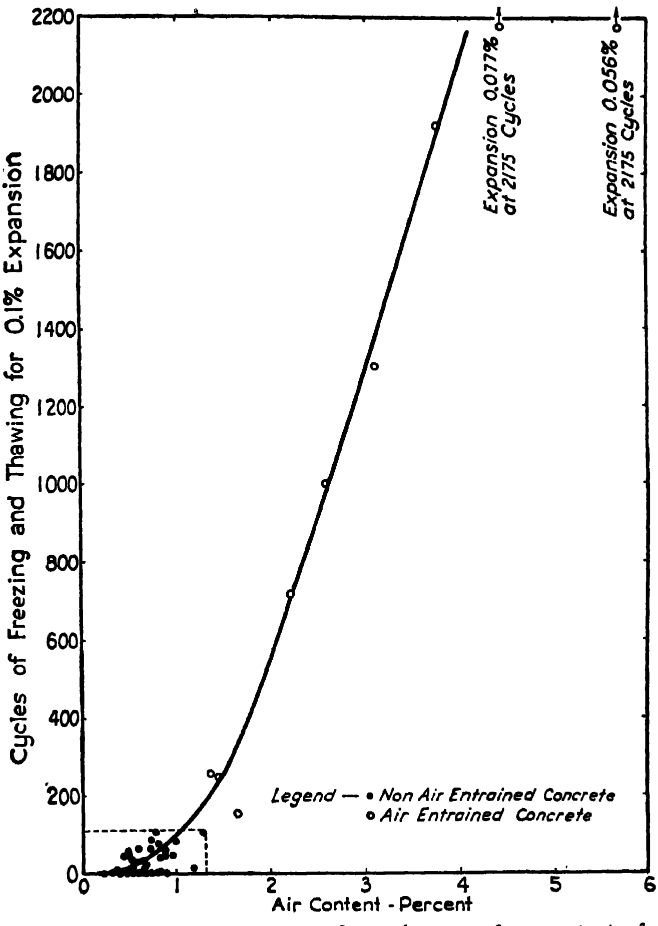


FIG. 105. Effect of air entrainment on the resistance of concrete to freezing and thawing. Aggregate sand and gravel graded 0 to 1½ in.; aggregates soaked in water 18 to 24 hours prior to use. Cement content, 4, 5½, and 7 sacks of cement per cubic yard. Slump, 2 to 3 and 5 to 6 inches. Specimens 3 by 3 by 11¼ in. cured 28 days moist and 3 days in water prior to test by freezing and thawing. (*Courtesy of Portland Cement Association, Chicago, Ill.*)

acceptable for other types of construction, although for reinforced-concrete structures an upper limit somewhat higher than 6 per cent has been permitted without detriment to the concrete. The 3 to 6 per cent air limits are intended to apply to concrete in which the volume

of mortar is approximately 0.5 to 0.6 per cent of the volume of the concrete. Where the volume of the mortar is appreciably more or less than this, the percentage of air should be increased or decreased accordingly.

Specifications for air-entraining portland cements produced by intergrinding controlled amounts of approved air-entraining agents with the cement are given in Specification C175 of the A.S.T.M. and in Federal Specification SS-C-192. The use of air-entraining cements and of air-entraining agents added at the mixer is increasing rapidly because of the improved characteristics they impart to the concrete.

Shrinkage and Expansion Due to Moisture. Concrete shrinks and expands with loss or absorption of moisture in much the same way as do wood and other materials. These changes in dimensions are independent of any changes which may occur from temperature or stress. It has been pointed out that when cement, water, and aggregates are mixed together to form concrete, only part of the water goes into chemical combination with the cement, the amount depending on the conditions and extent of the curing. The remainder is free to leave the concrete mass when exposed to a drying atmosphere. This causes a shrinkage to take place, the extent and rate of which depend upon the degree and rate of drying. Shrinkage ceases when the concrete is thoroughly dry. However, upon wetting, the concrete again expands, the amount of expansion depending on the total quantity of water absorbed. This process of shrinking and expanding is practically reversible; *i.e.*, a piece of concrete may shrink upon drying until all of the free water has left it but upon immersion may expand to practically its original length.

While the aggregates most commonly used in concrete are also subject to some shrinkage and expansion, the major portion of the volume change in concrete is due to that of the hardened cement paste. Consequently, the greater the quantity of paste in the mix, the greater will be the volume change that may be expected. The quality of the paste, as determined by the water-cement ratio, is also a very important item in shrinkage and expansion of concrete. Where a large quantity of water is used, a greater amount is free to leave the mass upon drying than where the quantity used is small, with the result that a greater shrinkage will be possible. Therefore, these two factors, the amount of cement paste in the mix and the amount of water in the paste, control the amount of shrinkage that can occur. The difference between a rich and a lean mix, however, is not so pronounced as might first be assumed, because, for a given workability, rich mixes require less water relative to the quantity of cement than lean mixes. For a given strength, a definite water ratio is required, but the amount of cement per unit volume of concrete can be varied con-

siderably by varying the quantity and gradation of the aggregates. For minimum shrinkage, the maximum quantities of aggregates consistent with proper handling and placing should be used.

The above discussion applies to shrinkage taking place after the concrete has hardened. However, there is also the possibility of shrinkage occurring, owing to loss of water during the first few hours while the concrete is still plastic. Rapid shrinkage at this stage will cause checking of the surface. Loss of water may be due to absorption by the aggregate particles, absorption by the forms or subgrade on which the concrete is placed, or evaporation from the surface. Shrinkage during the plastic stage can be overcome by preventing the evaporation of moisture, or its effects can be overcome by reconsolidation of the plastic material after the initial loss has occurred.

The volume changes taking place after the concrete has hardened should be taken care of in the design of the structure by proper spacing of joints and arrangement of reinforcing bars. For the average concrete, the maximum amount of shrinkage that may be expected in small unrestrained members subject to drying conditions, such as may be found in a heated building, will be about ¾ in. in 100 ft. In large masses, which lose water very slowly, such as dams or other massive structures exposed to the weather, the shrinkage due to this loss may be as little as 15/100 in. in 100 ft. or even less.

Contraction and Expansion Due to Temperature. Concrete expands or contracts with increase or decrease in temperature in the same manner as most engineering materials. The coefficient of thermal expansion of concrete varies with its composition and moisture content, an average value being about 0.0000055 for 1°F. The effects of changes in atmospheric temperatures are provided for by means of steel reinforcement and by appropriate spacing of expansion and contraction joints.

Of particular importance is the volume change which accompanies the rise and fall in temperature of massive concrete during hardening due to the liberation of heat by the hydration of the cement. Unless special precautions are taken to minimize the temperature change in such masses, cracks are likely to be formed as the concrete cools from its higher temperature to that of the surrounding atmosphere. These precautions consist of minimizing the amount and rate of heat liberation and of providing for the dissipation of as much heat as possible from the concrete during the early hardening period.

Use of Concrete for Fireproofing. Concrete makes excellent fireproofing material, for steel columns and girders and structures made of concrete are very resistant to destruction by fire. Under the action of heat the surface of the concrete is dehydrated, and the evaporation

of the water chemically combined with the cement keeps down the temperature of the inner layers of concrete. The dehydrated surface of the concrete is rendered weak and porous by the heat, but the injury rarely extends over an inch or two into the concrete; moreover, the dehydrated surface is an excellent heat insulator and affords increased protection to the inner layers of concrete. From 1½ to 2½ in. of good concrete is generally considered sufficient protection for structural steel work. In reinforced-concrete structures the metal reinforcement should be protected by not less than 1 in. of concrete in slabs and walls, and not less than 1½ in. in beams, girders, and columns, provided coarse aggregate is used which changes in volume a relatively small amount when exposed to high temperatures. A study of the action of reinforced-concrete buildings when subjected to fire, and fire tests of reinforced-concrete columns under load, indicated that aggregates made up of highly siliceous materials, such as sandstone, quartz, flint, and granite, are less resistant to the action of heat than aggregates consisting of limestone, calcareous gravel, trap rock, blast-furnace slag, expanded slag, cinders, burnt shale, or clay. When impractical to obtain aggregate of the more resistive grades, the protective covering should be ½ in. thicker and be reinforced with metal mesh having openings not exceeding 3 in., placed 1 in. from the finished surface. Experience and tests have shown that round columns are less seriously affected by fire than square columns.

One marked advantage which concrete possesses as a fireproofing material for steel lies in the fact that its coefficient of expansion is very nearly the same as that of steel, so that there is less danger of spalling off under the action of heat for concrete fireproofing than there is for fireproofing materials whose coefficients of expansion differ widely from that of steel.

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Questions

1. Define plain concrete; reinforced concrete.

2. What are the essentials for water to be used in mixing concrete? Is the water supply in your locality suitable for this purpose?

3. Define aggregate. Distinguish between fine aggregate and coarse aggregate.

4. Name materials commonly used as fine aggregate; as coarse aggregate.

5. Name the essential properties for a good concrete for (1) a dam, (2) a retaining wall exposed to sea water, (3) a highway pavement, (4) an outdoor swimming pool in Vermont, in Florida, (5) an indoor swimming pool, (6) culvert pipes, (7) a warehouse floor.

6. What is broken-stone concrete, cinder concrete, cyclopean concrete, gravel concrete?

7. What is a well-graded aggregate?

8. Define mortar; "workability" of concrete.

9. Why do specifications limit the maximum size of pieces of aggregate to be used in making reinforced concrete?

10. Name some undesirable ingredients in concrete aggregate and tell why each is undesirable.

11. What are voids? What are common values for percentage of voids in concrete aggregate?

12. Name some common arbitrary proportions of ingredients in concrete.

13. What proportions are in common use in your vicinity for concrete to be used for (1) columns in a storehouse, (2) reinforced concrete beams, (3) foundation walls for dwelling houses, (4) sidewalks? Have there been any failures? If so, were they due to poor proportioning of concrete?

14. Name undesirable ingredients in concrete aggregate. Are any of these troublesome in your vicinity? Does the concrete poured in your vicinity generally meet the A.S.T.M standards for limiting amounts of deleterious materials?

15. Why is it frequently advisable to screen and artificially adjust the proportions of different sized particles in sand and gravel? Is this done by the contractors in your vicinity?

16. What is water-cement ratio? Why does excess mixing water make weak concrete? How much may the strength of concrete be reduced by excess mixing water?

17. Describe the following methods of proportioning the ingredients of concrete: (1) maximum-density method, (2) surface-area method, (3) method by voids in mortar

and concrete, (4) fineness-modulus method, (5) proportioning by trial batches. Which, if any, of these methods are in use by your local contractors?

18. What is the limiting condition for the minimum water-cement ratio which can be used in mixing concrete?

19. Describe the slump test. What do its results show?

20. Outline the method of proportioning concrete by the trial-batch method.

21. Describe various methods of measuring cement, sand, coarse aggregate, and mixing water for a concrete mix.

22. Name sources of error in measuring concrete ingredients.

23. Describe the batch mixer for concrete. Discuss the effect of time of mixing on the strength of concrete.

24. What is "segregation" in wet concrete? What damage does it cause?

25. State precautions to be observed in placing concrete in molds; in bonding new concrete to old.

26. Why are special methods necessary in depositing concrete under water? Describe a method used.

27. What is a vibrator for concrete? How is it used? What are the advantages of vibrated concrete?

28. What precautions are to be taken in bonding new concrete to old concrete?

29. What is the effect of drying out of concrete during curing? Describe methods of curing which avoid drying out.

30. What is the effect of freezing temperature on freshly mixed concrete? What precautions should be used during the pouring of concrete in freezing weather?

31. Why must forms be left longer on floor slabs than on vertical walls?

32. What is the unit system of casting concrete? What are its advantages and disadvantages?

33. Why are concrete blocks made of a dryer consistency than that found in concrete poured into molds for a large structure?

34. What precautions should be taken in removing forms from a concrete structure?

35. Give the approximate ratio of compressive strength of concrete to tensile strength; to modulus of rupture; to strength under shear.

36. Name a job on which high-early-strength concrete might be used economically. Tell methods of securing high-early-strength concrete.

37. Discuss the purpose of using deformed reinforcing bars in concrete. Are such bars more effective than plain bars?

38. Judging by the allowable working stress for concrete given in Table XI(c), Chapter VII (or by reference 8 above, if that is available), how would the "factor of safety" for concrete structural members compare with "factor of safety" for structural steel?

39. What precautions are necessary to secure watertight concrete?

40. Discuss the use of waterproofing compounds and coatings for concrete.

41. Discuss the relation between the watertightness of concrete and its durability.

42. Describe the freezing and thawing test. What is the significance of its results?

43. How does concrete act as a fireproofing material?

44. What precautions should be taken when bonding new concrete to old?

45. Name two ways in which the surface of concrete is finished.

46. Why is very quick drying out injurious to concrete?

47. What general method is used for curing concrete?

48. How long should the forms of a concrete structure be left in place? Discuss.

49. Explain the "hump" in the curve shown in Fig. 96.

50. Are failures of concrete due to shearing stress frequent? Explain.

51. Under what conditions is the modulus of elasticity of concrete of importance in designing a concrete structure?

52. Name some factors which influence the durability of concrete.

53. What is air-entrained concrete? What improved characteristics can air-entraining impart to concrete?

54. How does the average coefficient of expansion of concrete compare with that of steel? Copper? Aluminum? Brick? Porcelain? Wood?

CHAPTER XVI

PLASTICS

By William N. Findley[1]

Definition and General Nature. It is particularly appropriate to introduce a chapter on plastics with a definition of the noun plastic, since as has been observed in previous chapters almost all engineering materials fall under the classification given by the dictionary for the adjective plastic. That is, most engineering materials are pliable and capable of being molded at some stage of their manufacture. The noun *plastic* is used to denote any one of a large and varied group of materials which consist of, or contain as essential ingredients, an organic substance of cross-linked or chain molecules of large size, and which, although solid in the finished state at ordinary temperatures, at some stage in their manufacture have been or can be formed into various shapes by flow—usually through the application singly or together of heat and pressure.

The plastics industry generally includes, in addition to relatively rigid materials, such materials as adhesives, rubber, and rubberlike products (elastomers). Although many of the substances that are used as adhesives and elastomers are identical with the more solid materials except for the amount and mode of application of certain ingredients, they will not be considered in this chapter, owing to their widely different uses and mechanical properties.

Some of the outstanding characteristics of most plastics are (1) light weight (less than half the weight of aluminum), (2) high dielectric strength (electrical insulation), (3) low heat conductivity (heat insulation), (4) colorability, and (5) resistance to certain solvents and other chemicals. The last two characteristics are not common to all plastics but depend upon the particular plastic.

Most plastics are synthetic organic compounds which derive their coherence and strength from large chain-linked *(macro) molecules* formed from one or more single molecules (monomers) to a *macro* molecule (*polymer*) by a chemical reaction called *polymerization*. The resulting large molecule has a very high molecular weight. Sometimes this production of a substance of high molecular weight from the monomer is

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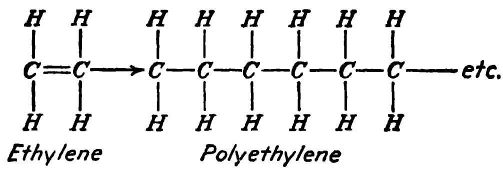
accompanied by the elimination of water. The resulting resins are referred to as *condensation polymers.* Usually articles made of such resins must be subjected to rather high pressure during the final stage of polymerization, owing to the steam pressure produced inside the resin by the temperature on the evolved water. Other resins are produced by *addition polymerization* in which water is not evolved. Some of these resins permit molding of articles under low pressures.

The simplest chemical form of polymer is made by polymerization of ethylene gas (obtained from petroleum or natural gas) into polyethylene. The chemical structure of this carbon (C) and hydrogen (H)



(*a*) Chemical structure of polyethylene.

(*b*) Scale model of polyethylene (straightened).

(*c*) Scale model of polyethylene (coiled).

FIG. 106. Structure of polyethylene polymer.

polymer is shown in Fig. 106(*a*). A Hirschfelder scale model of polyethylene is shown in Fig. 106(*b*), in which the dark spheres are carbon and the light spheres are hydrogen. This is a linear polymer and the polymerized molecules possess great flexibility owing to the absence of bulky atoms or groups of atoms fastened to the side of the chain. Its flexibility is illustrated by coiling the model around itself [see Fig. 106(*c*)].

Unstretched polyethylene sheet or film consists of a matrix of "crystallites" oriented at random. These crystallites are of roughly spherical shape, as shown by the electron micrograph (see Fig. 107). On stretching at elevated temperatures, the long-chain molecules tend to line up with the direction of stretching, so that a crystallization occurs which

shows, throughout the stretched material, X-ray diffraction patterns typical of crystalline materials.

Plastics may be divided into two general classes: (1) *thermoplastics*, which require cooling to harden them after softening by heat, and which may be resoftened and rehardened by successive heatings and coolings, and (2) *thermosetting plastics*, which are hardened by chemical changes due to heat or to a catalyst, or to both. Thermosetting plastics remain hardened without cooling and do not soften appreciably when reheated.

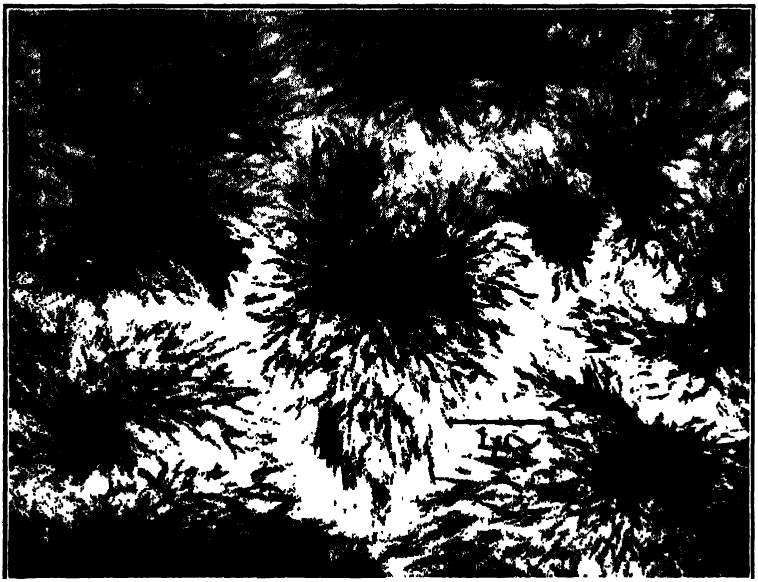


FIG. 107. Electron micrograph of an unstretched film of polyethylene. Magnification 13,000 times. (*Courtesy of Journal of Applied Physics. Micrograph by Alexander Brown, Carbide and Carbon Corp., South Charleston, W. Va.*)

It may be noted here that a catalyst is a chemical which accelerates a chemical reaction, apparently without taking part in it.

The sources of raw material for most plastics are the following natural substances: coal, petroleum, limestone, salt, sulfur, air, water, and cellulose from cotton and wood. Of course, this does not mean that some of these ingredients can be poured into a mixmaster, stirred well, baked for 2 hr., and from the oven emerges a pair of size 9½ nylons. Instead, the raw materials must undergo a large number of chemical decompositions and recombinations in order to produce usable plastics—just as is true in the manufacture of aluminum alloys and portland cement.

Types of Plastics. Table XXXV lists some of the most important types of plastics, together with some of their properties and uses. Many

TABLE XXXV. PROPERTIES AND USES OF COMMON PLASTICS
Courtesy of Plastics Catalogue Corporation, New York

A. THERMOSETTING PLASTICS

Property	Phenol-formaldehyde resin: Macerated cotton fabric or cord filler, molded	Phenol-formaldehyde resin: Mechanical grade, no filler, cast	Urea-formaldehyde, α-cellulose, molded	Melamine-formaldehyde, asbestos, paper or fabric, laminate	Polyester, glass fiber, mat, laminate	Silicone glass fabric, laminate	Cold-molded[2] cement binder, asbestos-filled	Hard rubber,[3] no filler
Compression molding pressure, thousand lb. per sq. in.	2.00–8.00	0	2.00–8.00	1.00–1.80	0.01–0.15	1.00–2.00	1.00–10.00	1.20–1.80
Specific gravity	1.34–1.47	1.25–1.30	1.45–1.55	1.75–1.85	1.5–1.8	1.6–1.8	1.6–2.2	1.14
Tensile strength, thousand lb. per sq. in.	2–9	4–7	6–13	6.5–12	10–20	10–25	1.6–2.2	8–10
Elongation, % in 2 in.	0.4–0.6	Very small	0.5–1.0	Very small	Very small	Very small	Very small	5–7.5
Modulus of elasticity in tension, hundred thousand lb. per sq. in.	9–13	5–7	12–15	16–39	10–19	20	... ...	3.0
Compressive strength, thousand lb. per sq. in.	15–30	15–20	25–35	27–50	30–50	35–46	16	8–12
Impact strength, Izod test on ½ × ½ in. notched bar, ft.-lb. per in. width of notch	1–8	0.3–0.4	0.24–0.36	0.7–5.0	11–25	5–22	0.4	0.5
Hardness, Rockwell[1]	M 110–120	M 70–110	M 115–120	M 110–115	M 90–100	M 100	M 75–95	HR 95
Highest usable temperature, continuous °F	250	250	170	225–245	300–400	400–480	900–1300	....
Thermal conductivity, $10^{-4}\frac{\text{cal}}{(\text{sec.})(\text{cm.}^3)(°\text{C.})}$	4–7	3–5	7–10	10–17	8–12	3.5	....	2.9
Thermal expansion $10^{-5}\frac{\text{in.}}{\text{in. °C.}}$	1–4	8–11	2.5–4.5	2.0–4.8	1.0–3.0	0.5	....	7.7
Dielectric strength, short time ⅛ in. thickness, volts/mil	200–400	....	300–400	40–150	250–400	200–480	45	470
Water absorption, 24 hr., ⅛ in. thick, %	0.04–1.8	0.2–0.4	0.4–0.8	1–5	0.3–1.0	0.2–0.7	0.5–15	0.02
Effect of strong acids	Decomposed by oxidizing acids	Decomposed by oxidizing acids	Decomposed	Decomposed	Some attack	Very slight	Decomposed	Attacked by oxidizing acids
Color possibilities	Limited	Limited	Unlimited	Limited	Unlimited	Limited	Gray and black	Limited
Common uses	Serving trays, radio cabinets electrical parts	Punches and dies	Tableware, electrical controls, housings	Aircraft structural parts, high-strength electrical insulation, electrical parts, stove switches	Aviation and automotive structures, decorative applications	High-temperature-resisting electrical insulation	Arc shields, terminal insulators, electric heater elements	Beakers, funnels, etc., for chemicals, combs

[1] Rockwell scales: M, ¼ in. diam. ball, 100 kg. major load; HR (hard rubber), ¼ in. diam. ball, 60 kg. major load.
[2] The cement binder is not strictly a thermosetting material but is set by chemical combination with water from steam (hydration).
[3] Hard rubber is not usually classified as thermosetting but as vulcanizing.

TABLE XXXV. PROPERTIES AND USES OF COMMON PLASTICS. (*Continued*)

B. THERMOPLASTICS

Property	Shellac	Polyethylene	Polymonochloro trifluro ethylene	Vinylidene chloride molding	Polystyrene	Methyl methacrylate, cast	Polyamide (nylon) molding	Cellulose acetate molding	Cellulose nitrate (pyroxylin)
Injection molding pressure, thousand lb per sq. in.	1.00–1.20	8–15	20–60	10–30	10–30	....	10–25	8–32	
Specific gravity	1.1–2.7	0.92	2 10	1.65–1 72	1.05–1.07	1.18–1.20	1.14	1.27–1.37	1.35–1.40
Tensile strength, thousand lb. per sq. in.	0.9–2.0	1.5–1.8	5.7	3–5	5–9	6–7	7–9	1.9–8.5	7–8
Elongation, % in 2 in.	....	50–400	28–36	20–250	1–3.6	2–7	40–100	6–50	40–45
Modulus of elasticity in tension, hundred thousand lb. per sq. in.	5–6	0.19	1 9	0.5–0.8	4–6	3.5–5	2.6–4	0 86–4 0	1.9–2.2
Compressive strength, thousand lb. per sq. in.	10–17	....	32–80	7.5–8.5	11.5–16	11–19	7.2–13	13–36	22–35
Impact strength, Izod test on, ½ × ½ inch notched bar, ft.-lb. per in. width of notch	2.6–2.9	Less than 16	3 6	0.3–1.0	0.26–0.50	0.4–0 5	1 0	0.4–5.2	5–7
Hardness, Rockwell[1]	....	R 11	R 110–115	M 50–65	M 65–90	M 90–100	M 111–118	R 50–125	R 95–115
Highest usable temperature continuous °F	150–190	212	390	160–200	150–205	140–200	270–300	140–220	140
Thermal conductivity, $10^{-4} \frac{\text{cal}}{(\text{sec.})(\text{cm.}^3)(°\text{C.})}$	....	8	1 4	3	2 4–3 3	4–6	5.2–5.5	4–8	3.1–5.5
Thermal expansion $10^{-5} \frac{\text{in.}}{\text{in}°\text{C.}}$	....	16–18	4 5–7.0	19	6–8	9	10–15	8–16	8–12
Dielectric strength, short time, ⅛ in. thickness, volts/mil	200–600	460	2500	350	500–700	450–500	385–470	250–365	300–600
Water absorption 24 hr., ⅛ in. thick, %	0–0 1	Less than 0.01	0 00	0–0.1	0 03–0 05	0 3–0.4	0 4–1.5	1 9–6 5	1.0–2.0
Effect of strong acids	Deteriorated	Attacked by oxidizing acids	None	Highly resistant	Attacked by oxidizing acids	Attacked by oxidizing acids	Attacked	Decomposed	Decomposed
Color possibilities	Limited	Unlimited	Unlimited	Extensive	Unlimited	Unlimited	Unlimited	Unlimited	Unlimited
Common uses	Phonograph records, electrical insulation	Bottle stoppers, flexible bottles, wire insulation, textiles, tablewear	Filter disks, insulators, gaskets	Screening, chemical tubing, auto seat covers	Electrical insulators, battery boxes, lenses, toys, boxes	Windows, furniture, dentures, picture frames	Bearings, cups, fabrics, bristles	Fountain pens, tools, toys, spectacles packaging	Packaging, foils, glazing materials, photographic film

[1] Rockwell scales: M, ¼ in. diam. ball, 100 kg. major load; R, ½ in. diam. ball; 60 kg. major load.

types of plastics are not included in this table and many new types may be synthesized in the future.

Of the thermosetting plastics, the phenol-formaldehyde compounds were the first to be synthesized, being made by Baekeland in 1909 from phenol and formaldehyde. This material, bakelite, is still one of the most widely used plastics. Urea-formaldehyde and melamine-formaldehyde resins have somewhat similar properties to those of phenol-formaldehyde, but have unlimited color possibilities and are odorless and tasteless, whereas the phenols are limited to dark colors. Three of the common thermosetting plastics—hard rubber, casein-formaldehyde, and asphalt cold-molding binder—are natural rather than synthetic polymers. Of the three types of binding agents used in cold-molding materials, only one, phenol-formaldehyde, really fits the definition of plastics given above. The other two types are asphalt and silica-lime cement. The latter material is an *inorganic* compound and is not a high polymer.

Cold-molding compounds are filled with about 90 per cent asbestos and are used for high-temperature applications. Hard rubber has been used extensively in the plastics industry since Goodyear's discovery of vulcanization. The chief disadvantages of hard rubber for molded articles are that the sulfur used to vulcanize the rubber corrodes metal and the rubber is discolored by sunlight. A silicone polymer offers a considerable improvement in heat resistance over other resins, both for application in plastics and for lubrication.

Thermoplastic materials include both synthetic polymers and the natural polymer, shellac. Natural polymers were the first to be used as commercial plastics. Shellac is a combination of several different chemicals secreted by small tree lice found in central India. It is used in the original form after some refining operations. Cellulose, which is not thermoplastic in its natural form, is obtained from wood flour and cotton linters. Cellulose is used by itself as a plastic (cellophane and vulcanized fiber) after a chemical regeneration to consolidate the original fibers into a more homogeneous substance. When treated with certain chemicals, cellulose is transformed into other widely used thermoplastics, such as cellulose nitrate (celluloid or Pyroxlyn) and cellulose acetate. Among the synthetic polymers are vinylidene chloride, widely used in the form of flexible tubes and pipes; methyl methacrylate, universally used for cockpit enclosures in military aircraft; polystyrene, widely used for cheap toys and one of the best electrical insulators; polyamide or nylon, chemistry's gift to women; polyethylene, used for flexible bottles and stoppers; and "fluorine-substituted polyethylenes," which are polymers of chemical structure similar to that of polyethylene except that fluorine atoms either replace all the hydrogen atoms, or three

out of four of them, and the fourth is replaced by a chlorine atom. Fluorine-substituted polyethylenes offer excellent resistance to high temperatures and to chemical attack.

Methods of Forming and Fabricating Plastics. Most of the methods used in the forming and fabricating of plastics have their counterpart in the processing of other engineering materials. *Casting*, for example, is a method used for forming cast iron, concrete, etc., as well as some plastics. Casting of plastics is a simple procedure using low-cost lead-antimony dies (molds) for making novelties, or molds of sheet metal and molding clay or plaster of paris for use in casting large plastic dies and punches to be used in forming sheet metal for aircraft skin sections. Both thermoplastic and thermosetting plastics may be cast. Obviously no pressure is used in casting processes so that resins must be especially selected if they are to be formed by casting.

Compression molding is most widely used in molding thermosetting compounds and requires the application of pressure to a molding compound placed in a cavity in heated platens of a press. Thermoplastics may be compression-molded, but the mold must then be cooled after each molding before the article is removed from the press. This increases the time required and is wasteful of steam for heating the molds. Multiple-cavity dies are often used to increase the number of articles produced in a given loading cycle. Often thermosetting compounds are introduced into the hot press in the form of tablets or blanks roughly molded to shape (preformed) by compressing the molding compound in a cold press.

Injection molding is one of the most widely used and most rapid methods of producing articles of intricate shape. It is analogous to the method of die casting which is used for producing similar intricate parts of zinc, magnesium, and aluminum (see page 130).

In the injection-molding process, pellets of thermoplastic are fed into a pressure chamber. A plunger then compresses the material and forces it into a heating chamber where it is progressively heated to a uniform temperature. The thermoplastic emerges through a nozzle in a thoroughly softened condition and is then forced into a cold mold where pressure causes it to take the shape of the cavity. The plastic is quickly cooled by the cold mold, which is then opened and the part ejected.

Cold molding is more economical than most methods of molding, owing to the fast molding cycle. The molded articles are then baked in an oven for several hours or are treated under steam pressure, if the binder is of the cement type.

Transfer molding is used to mold thermosetting materials when the part is to include delicate inserts or when the shape of the mold cavity is

complex. In this method the molding compound is heated under pressure in a separate cavity in the press until it is soft enough to flow readily. The compound is then ejected from the original cavity into the cavity in which the part is formed. Direct compression molding would cause the hard molding compound to be pressed against inserts with possible breakage or dislocation and with incomplete fill of complex cavities.

Preheating with a high-frequency electrostatic field is often used to speed the operation of compression or transfer molding of thermosetting materials by quickly heating preforms or tablets of the molding compound to a temperature at which they are soft or puttylike before being placed in the molding press. The heating is due to internal friction in the preform caused by repeated stressing of the material under the action of the alternating electrostatic field. This method of heating is also applied to the bonding of wood with thermosetting adhesives and to the heating of thermoplastic sheet for forming operations.

Extruding of thermoplastic plastics is a process widely used for producing rods, tubes, and other cylindrical shapes. Extruding of plastics differs only in details from the extrusion of light metals and lead alloys.

Laminating is used to produce hard boards or sheets of resin-impregnated paper, wood veneers, or fabrics. Fabrics such as canvas, rayon, asbestos, and glass fabric are used to produce plastics of high-strength properties. Laminates may be made into stock sizes of flat sheets under high to medium pressure in a press, or they may be made in special shapes such as rowboat hulls by the *bag-molding* process. This process involves building up the individual resin-coated fabric or veneer over a form, inserting the assembly into a large rubber bag, withdrawing the air from the bag, and subjecting the bag and contents to steam pressure in a cylinder known as an *autoclave*. With certain resins (called contact resins) the laminate may be built up on a form and cured in an oven without the use of any more than contact pressure.

Drawing and post forming of plastic sheets is a method of fabrication that is increasing in importance. Deep drawing of thermoplastic sheets or post forming of thermosetting laminates is very similar to the deep-drawing processes used in metal forming except that the plastic sheets must be heated to certain temperatures before drawing. In thin thermoplastics, domes as deep as 18 in. may be drawn. The term post forming derives from the fact that the laminate is reformed in this operation after it has been fully cured as a thermosetting laminate.

Blowing of thermoplastics is accomplished in much the same manner as blowing of glass in the glass industry. Blowing techniques are used for fast, cheap production. Completely automatic machines are available

which start with the molding compound, heat it to the correct temperature, and blow it into a bubble which is forced against the walls of a mold where the part is cooled and finally ejected from the mold. Other blowing techniques are similar to deep-drawing in that a sheet of the thermoplastic is heated, clamped around the edges in a press, and drawn by means of air pressure rather than by a die as in deep-drawing.

Machining and Cementing. In addition to the methods of fabrication of plastics mentioned above, electrical insulating parts and other items are made by machining from sheet, rod, or tube stock. Laminated plastics may be riveted, or cemented together, or, in the case of thermoplastics, may be welded by the use of solvents, hot plates, or heated rolls. Some may also be torch-welded in a manner very similar to torch-welding of metals.

Constituents of Molding Compounds for Plastics. Into the make-up of the molding compound from which a finished plastic is to be made, various constituents enter. In choosing these constituents and in blending them there are two conflicting demands to be met: (1) the material should flow readily while being molded to shape and (2) the finished product should be strong and usually stiff. These conflicting demands are especially trying in the case of thermosetting plastics.

The prime constituent necessary in a molding compound is the *resin or binder*, which cements the various constituents together. Binders (resins) are discussed above and are listed in Table XXXV. The binder may be a cellulose derivative, phenolic, urea, shellac, or many of the other types indicated in the table. The thermoplastic binder materials are in a polymerized form before heating, while the thermosetting binders are added in an unpolymerized (or partially polymerized) condition, and polymerization takes place upon heating by the addition of a catalyst, as they are pressed or injected into molds.

A second ingredient used especially in thermosetting molding compounds is a filler, whose chief function is to provide the plastic with properties that the binder itself does not possess or to lower the cost of the article. For example, shredded textile materials improve the resistance of thermosetting plastics to shock.

A third ingredient in a molding compound is a plasticizer, generally an oily liquid. Plasticizers are used mainly with thermoplastics to improve the flow qualities, impact resistance, or flexibility of the material. For example, methyl and ethyl phthalates are frequently added to cellulose acetate for this purpose.

In thermosetting plastic molding compounds, a catalyst is frequently added to accelerate the polymerization reaction. For example, in phenolic resins, hexamethylenetetramine (hexa) is frequently added.

Under heat this breaks down into formaldehyde and ammonia. The latter acts as an alkaline catalyst.

To prevent molding compounds from sticking to the molds and to reduce internal friction in the molding compound, lubricants, such as stearates or graphite, are added as ingredients. Dyes and pigments are frequently incorporated in molding compounds to impart color to the finished product.

Effect of Service Conditions on Mechanical Properties. The dissimilarities between the properties of plastics and those of metals are often pointed out, but it seems to the writers that the similarities between the mechanical properties of plastics and those of metals are more striking then the dissimilarities, particularly when the difference in composition is considered. Metals are inorganic and crystalline. Plastics are organic and usually amorphous. Yet the stress-versus-strain relationships are similar, as are the behaviors under impact, and the response to changes in temperature. Repeated stress produces fatigue cracks in both types of material, and elevated temperatures combined with steady loads produce creep in much the same manner in both plastics and metals. The differences are mostly in degree, not in kind of response. Speed of testing, humidity of air, small changes in temperature, tendency to absorb water, and creep at low stresses—these are usually *minor* factors in judging the mechanical properties of most stress-carrying metals at room temperature, but they may be *major* factors for plastics. Table XXXV shows characteristics and uses of eight typical thermosetting plastics and of nine typical thermoplastics.

As an illustration of some of the effects of different service conditions (temperature, humidity, vibration, sunlight, etc.) on the mechanical properties of plastics, there are given here the results of tests made by the writer and by other investigators. Figure 108 shows stress-strain diagrams for tension tests to fracture of cellulose acetate, using various speeds of the pulling head of the testing machine. These speeds of head may be considered as roughly proportional to the rate of strain in the specimen, since the specimens were all similar in size and shape, the grips were the same for all specimens, and only one testing machine was used.

The fairly well defined "upper" and "lower" yield points, and the increase of yield point and of tensile strength with increase of speed of testing are to be noted. No very clear relation between elongation at fracture and speed of testing is shown.

Figure 109 shows the results of tension tests of methyl methacrylate. Tests were conducted with different values of strain rate. In these tests the testing machine was equipped with an automatic control of the

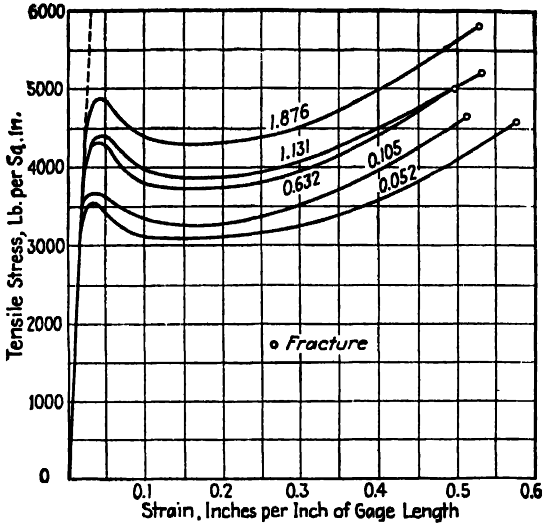


Fig. 108. Stress-strain diagrams for tensile tests of specimens of cellulose acetate sheeting. Figures on the diagram indicate the speed of the pulling head of the testing machine in inches per minute. (*Courtesy of American Society for Testing Materials.*)

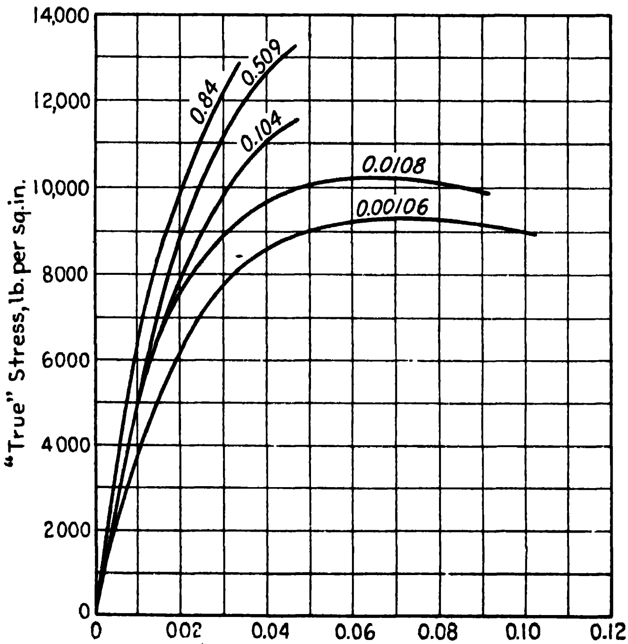
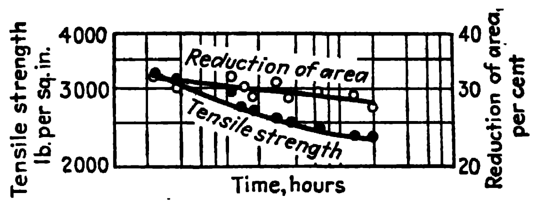
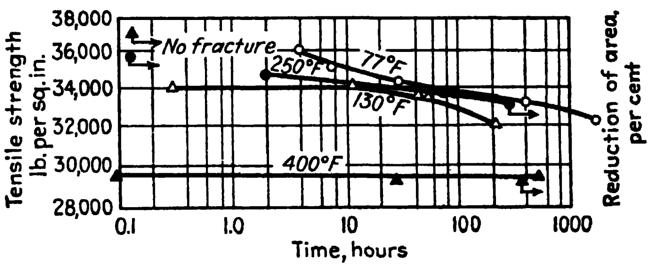


Fig. 109. **Stress-strain diagram for specimens of methyl methacrylate. Figures on the diagrams indicate the "true" strain rate in inches per inch per minute.** (*Courtesy of A. G. H. Dietz.*)

"true"[1] strain rate, so that the rate of straining was constant during the test. In the tests shown in Fig. 109, the strain measured is "true" strain and the stress is "true" stress. However, the direct comparison of stress-strain diagrams in Fig. 108 and Fig. 109 gives a fair idea of the relative extensions of the cellulose acetate and the methyl methacrylate. The initial modulus of elasticity (modulus of elasticity for low stresses) remained approximately constant. However, there was a distinct tendency toward increased *strength* and decreased elongation at fracture.



(*a*) Cellulose acetate.



(*b*) Melamine resin glass fiber laminate.

FIG. 110. Results of tests to fracture under long-continued load of cellulose acetate specimens and of specimens of melamine resin glass fabric laminate. (*Courtesy of American Society for Testing Materials and of National Advisory Committee for Aeronautics.*)

Certain plastics (polyethylene and nylon, for example) undergo abrupt "necking down" in the yield region. This "necked-down" region may be pictured as "feeding" on the un-necked material and in some cases fracturing only after a very long extension (sometimes as high as 200 per cent or more). During this process the chain molecules are stretched from a random orientation into a parallel configuration, tending to produce crystallization and increased strength. Tenacious textile fibers are produced in a manner quite similar to this stretching process.

[1] The "true" strain is equal to $\log_e l/l_0$ in which l_0 is the gage length under zero stress, and l is the length of the stretched gage length under the applied load. The "true" stress in a tension specimen is equal to the load divided by the actual minimum area of cross section under the applied load.

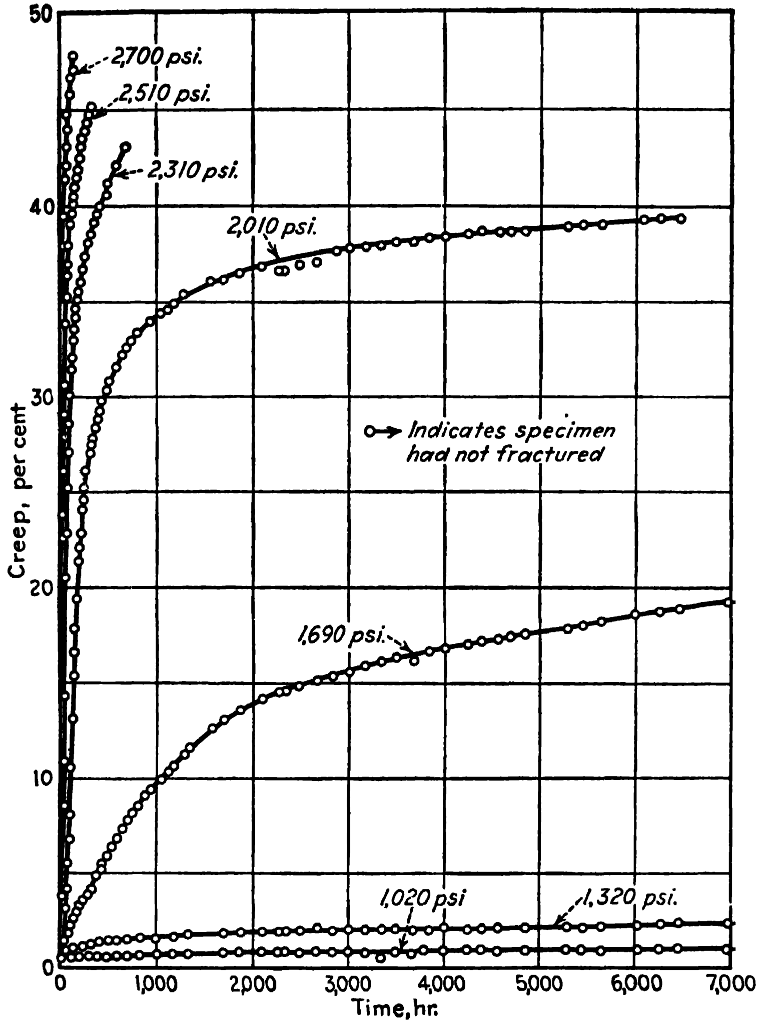


FIG. 111. Results of long-time creep tests of cellulose acetate sheeting at several values of stress. The tests were conducted under constant loads, constant temperature (77°F.), and constant relative humidity (50 per cent). (*Courtesy of American Society for Testing Materials.*)

Figure 110 shows the decrease of tensile strength and of ductility with increase of time under a steady load of specimens of cellulose acetate. In Fig. 110(*b*) the tensile strength of specimens of melamine glass fabric is seen to decrease as temperature increases. The strength-time and strength-ductility diagrams are quite similar to diagrams obtained for steel at high temperature and for lead alloys at room temperature. Obviously, the tensile strength of a plastic as given by a short-time

tensile test is not necessarily a safe guide for its strength under long-continued steady load.

The creep behavior of plastics under long-continued steady load is illustrated in Fig. 111 by creep-time diagrams for specimens of the same cellulose acetate mentioned previously, and in Fig. 112 for a high-strength melamine glass fabric laminate. Note the relatively

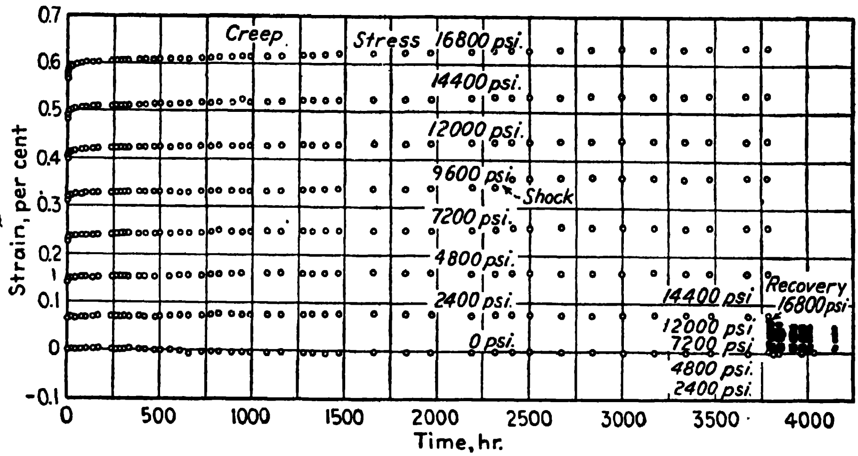


FIG. 112. Creep and recovery versus time for tension creep tests at 77°F. on melamine–glass fabric laminate. (*Courtesy of American Society for Testing Materials.*)

large creep of the cellulose acetate (about 38 per cent for 3,000 hr. under 2,000 lb. per sq. in. tensile stress) as compared with a creep of about 0.08 per cent for the melamine glass fabric under about the same time and stress.[1]

Figure 114 shows the results of fatigue tests of specimens of cellulose acetate under cycles of completely reversed bending stress. The tests show fairly well-defined endurance limits: 1,480 lb. per sq. in. for the

[1] Figures 108 to 112, 118, and 119 show the marked dependence of the strength and deformation of plastics on the temperature and rate of straining both in tension tests and in creep tests. Thus it might be expected that this dependence stems from the same basic causes for both types of test. It has been possible to formulate mathematical equations to describe the creep curves of some plastics and some metals. In these equations, the absolute temperature appears exponentially, the time appears as a power function, and the stress appears as a hyperbolic-sine function (see reference 8 at the end of this chapter).

From equations of this type, it has also been found possible to derive equations describing the stress-strain curve as a function of strain rate and temperature. Such a derived curve is shown in Fig. 113, together with data for a tensile test. The agreement of the curves, at least for the lower stress range, shows some tendency to confirm the common origin of the strain rate dependence of both creep test results and tensile test results (see reference 7 at the end of this chapter).

round specimens, 1,070 lb. per sq. in. for the flat specimens, and 540 lb. per sq. in. for the notched flat specimens. There seems to be a distinct "shape" effect as shown by the difference between results for the round and for the flat specimens.[1] The "fatigue notch factor" in the notched

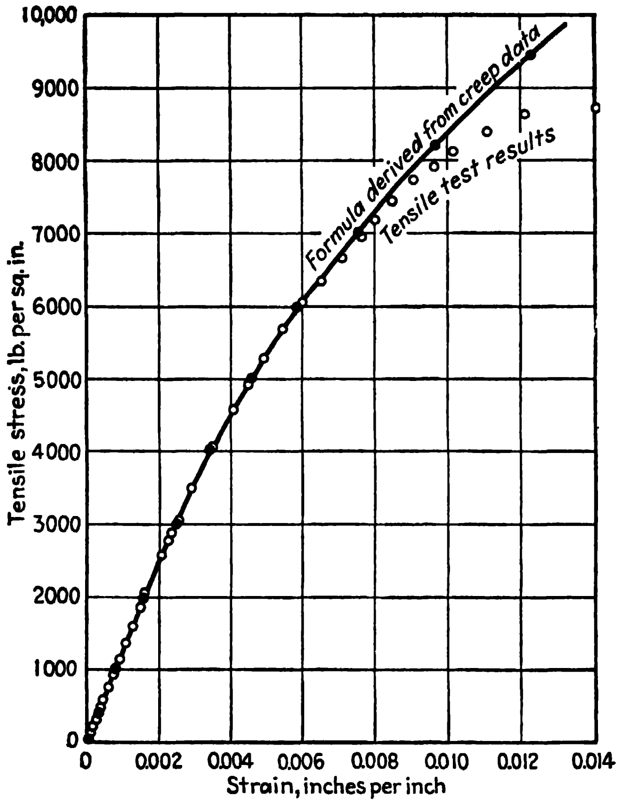


FIG. 113. Relation between stress-strain data from a tensile test of a canvas laminate and a hyperbolic-sine formula derived from creep data for the same laminate. (*Courtesy of First National Congress of Applied Mechanics.*)

specimens was then 1,070/540 = 1.98, a value not very different from that found for medium-strength steel.

In Fig. 115 are shown results of fatigue tests of a rayon fabric laminate. *S-N* diagrams for both notched and smooth specimens for tests in a rotating cantilever (complete reversal of stress) machine are shown. The difference in slope of the *S-N* diagrams for notched and smooth specimens is noteworthy. Under small numbers of cycles of

[1] The round specimens were 0.29 in. in diameter, the flat specimens were 0.5 by 0.31 in. in cross section: in the notched specimens, there was a 45-deg. notch 0.02 in. deep, with a radius of 0.01 in. at its root.

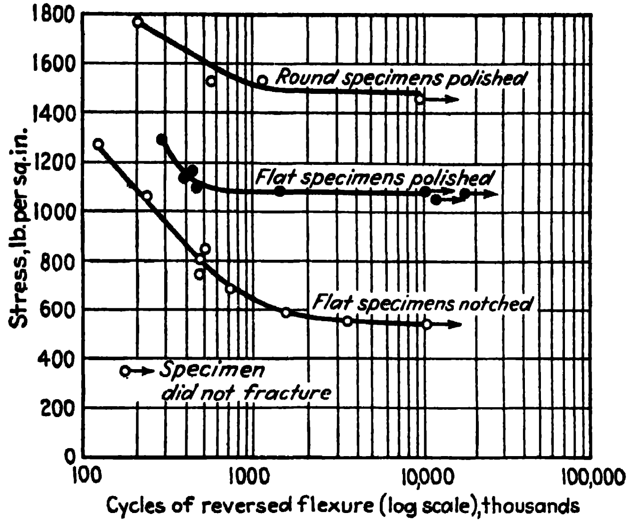


FIG. 114. S-N diagrams for fatigue tests of cellulose acetate under cycles of reversed flexure. The stress indicated is the maximum stress during a cycle. Tests were made at 77°F. and 50 per cent relative humidity.

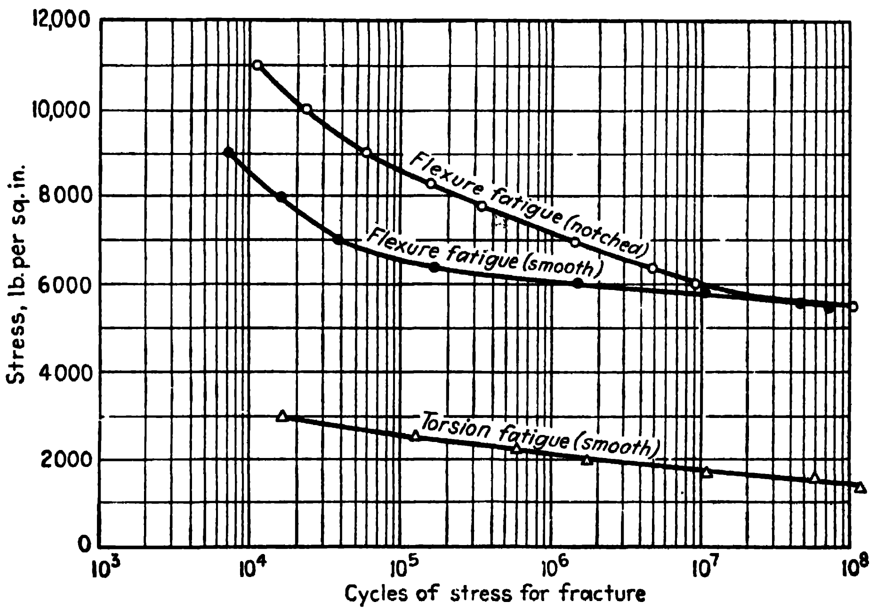


FIG. 115. *S-N* **diagrams for tests of a rayon laminate. Fatigue tests made on rotating-cantilever fatigue testing machine for flexure tests and on a torsion fatigue testing machine for torsion tests of smooth specimens.**

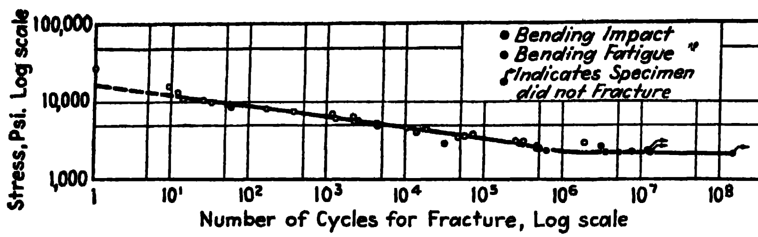


FIG. 116. *S-N* diagrams for repeated impact and fatigue tests of cellulose acetate in bending. Log-log plotting; temperature 77°F.; relative humidity 50 per cent. Range of stress approximately from zero to a maximum. The stress plotted is the maximum stress during a cycle. (*Courtesy of American Society for Testing Materials.*)

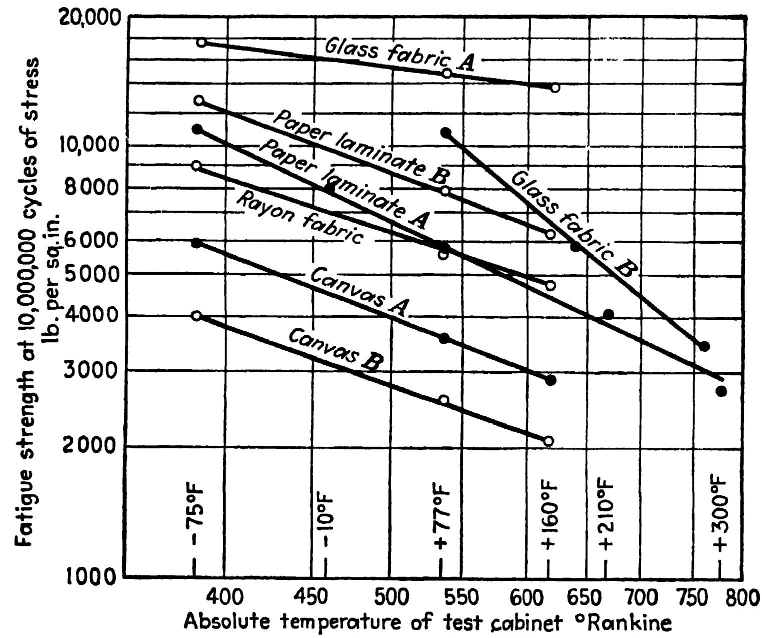


FIG. 117. The effect of temperature on the fatigue strength of several laminates at 10,000,000 cycles of reversed stress. The glass fabrics were molded with a polyester resin and the other laminates with a phenolic resin.

stress, the fatigue strength of the notched specimens is somewhat *higher* than that of the smooth specimens, but the *S-N* diagrams of notched and smooth specimens of the rayon fabric seemed to come together at about 20,000,000 cycles of stress. Similar results have been observed in other laminates. Explanations which have been advanced for the high strength of the notched specimens include differences in temperature from internal friction, combined stresses at the root of the notch, and

differences in mode of propagation of cracks in smooth and in notched specimens.

The results of falling-ball type of repeated-impact tests on a cellulose acetate are seen in Fig. 116, together with fatigue tests of the same material. Apparently the mechanism of formation of a crack under repeated stress is the same, irrespective of the mode of application of the stress.

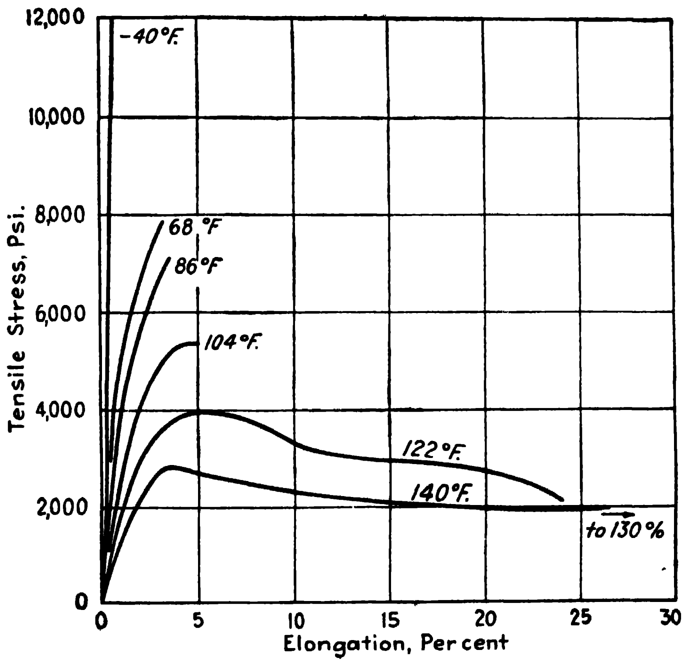


FIG. 118. Effects of temperature on stress-strain properties of polymethylmethacrylate. (*Courtesy of T. S. Carswell and H. K. Nason and American Society for Testing Materials.*)

Changes in temperature cause marked changes in the fatigue of some plastics, as shown in Fig. 117 for tests of several laminates. The fatigue strength S_f can be expressed as a function of absolute temperature T for all the laminates shown in Fig. 117, by an equation of the form $S_f = kT^{-q}$ in which k and q are constants. The effect of temperature on the stress-strain characteristics of polymethylmethacrylate in tension is shown in Fig. 118, and on the stress-strain characteristics in compression of a silicone–glass fabric laminate at various temperatures is shown in Fig. 119. Note that as the temperature is decreased, the ductility diminishes until it is practically zero, the stiffness increases, and the ultimate strength increases.

Compare Fig. 118 with Fig. 109 and note the similarity between the effect produced by increasing the temperature and that produced by reducing the strain rate. Temperature affects the impact strength of plastics in a manner similar to its effects on metals: low temperatures promote brittleness (low impact strength); high temperatures promote ductility (high impact strength). Figure 120 illustrates this behavior for thermosetting molding materials. At temperatures above

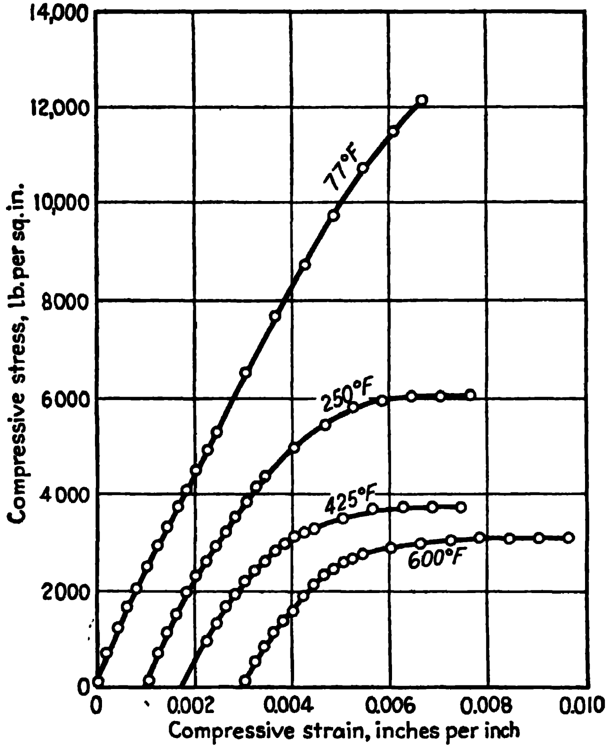


FIG. 119. Stress-strain diagrams of a silicone resin glass fabric laminate in compression at various temperatures. (*Coutesy of National Advisory Committee for Aeronautics.*)

approximately 160°C., these plastics begin to decompose so that the impact strength decreases rapidly at higher temperatures.

The behavior ot both plastics and metals at fracture changes from ductile (with large absorption of energy) to brittle (with small energy absorption) as the temperature is lowered or the strain rate is increased to a point at which the load is applied so fast that flow cannot occur. The velocity of straining at this "brittle point" has been found for some materials to be related to the temperature as follows:

$$V_c = Ce^{A/T_c}$$

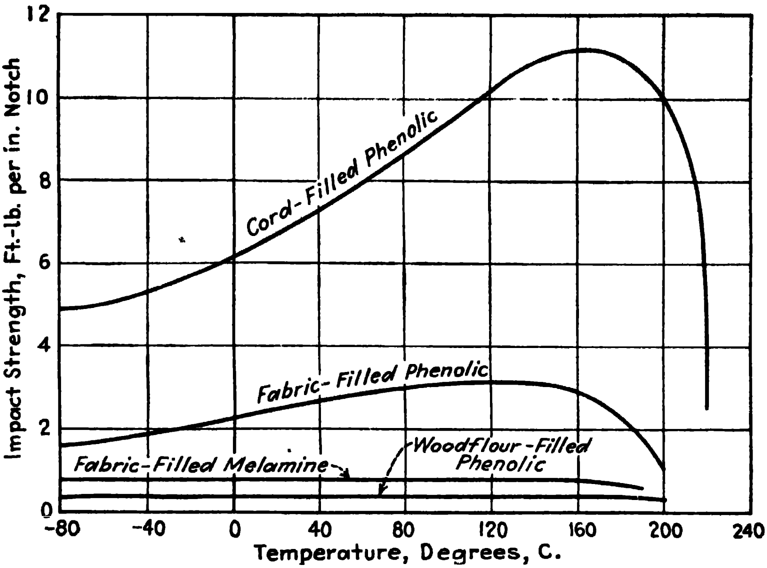


FIG. 120. Effect of temperature on the impact strength of several plastics. (*Courtesy of T. S. Carswell and H. K. Nason and American Society for Testing Materials.*)

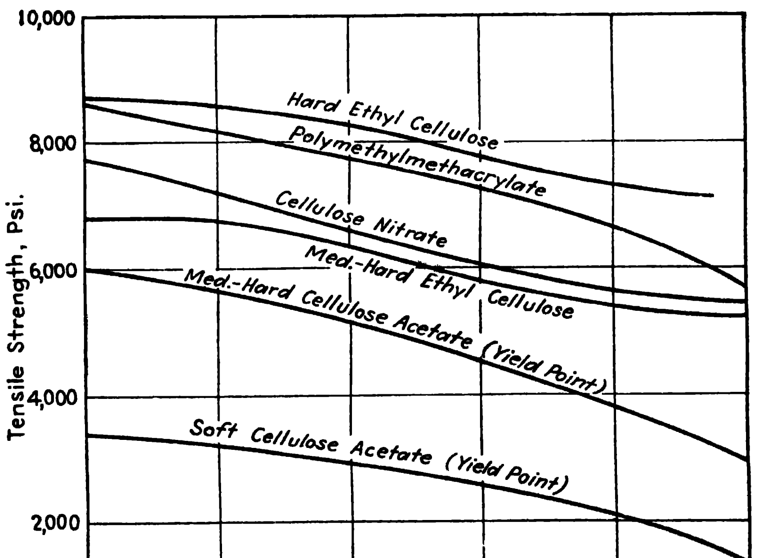


FIG. 121. Effect of relative humidity on the tensile strength of several thermoplastics. (*Courtesy of T. S. Carswell and H. K. Nason and American Society for Testing Materials.*)

in which V_c is the critical velocity of strain, T_c the critical temperature to produce brittleness, e the base of the Naperian system of logarithms, and C and A are constants.

Different relative humidity (with resulting differences in moisture content of many plastics) plays an important role in determining the load-resisting and electrical characteristics of most plastics. The effect of relative humidity on the tensile strength of several thermoplastics is

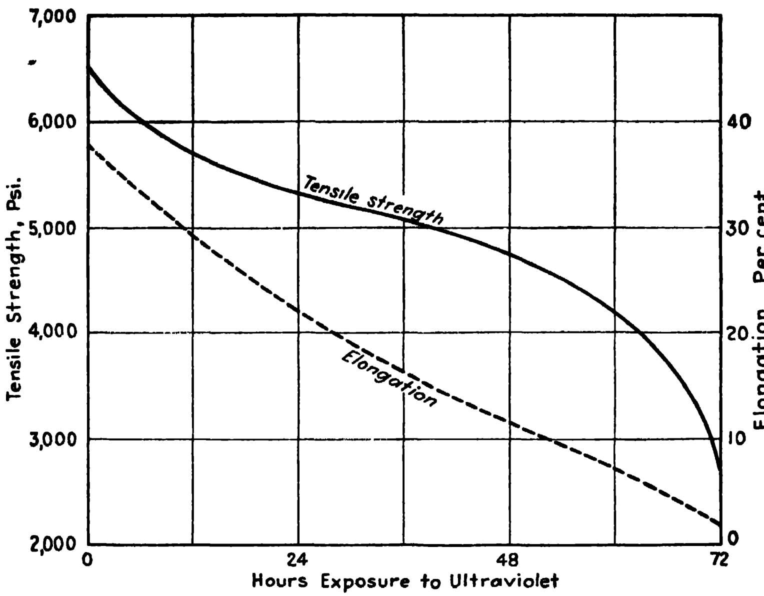


FIG. 122. Effect of exposure to ultraviolet light on the tensile properties of cellulose nitrate sheet plastic. (*Courtesy of T. S. Carswell and H. K. Nason and American Society for Testing Materials.*)

shown in Fig. 121. In general, increasing relative humidity (moisture content) decreases strength properties of plastics in which either the resin or the filler is hygroscopic.

Exposure to sunlight (ultraviolet light, in particular) has a deteriorating effect on many plastics or on the dyes and pigments used in coloring them. The effect of exposure to ultraviolet light is especially pronounced on cellulose nitrate, as shown by the decrease in tensile strength and ductility in Fig. 122.

Other service conditions to be considered in selecting a plastic for a particular application are attack by fungus, rats, roaches, etc.; the action of solvents and chemicals; and oxidation.

Comparison of Plastics and Metals When Weight Is a Prime Factor. Most plastics develop lower strength and stiffness values than do the

common stress-carrying metals. However, in applications in which the weight of a part is an important factor plastics make a better showing than they do when the comparison of strength or stiffness is based on equal size of part.

The weight (or specific gravity) of materials may be taken into account when comparing their suitability for a given structural application by dividing the appropriate strength or stiffness value of each material by the

TABLE XXXVI. STRENGTH-WEIGHT RELATIONSHIPS FOR PLASTICS AND SOME COMMON STRUCTURAL MATERIALS

Material	Specific gravity	Tensile strength, lb. per sq. in.	$\frac{\text{Tensile strength}}{\text{Specific gravity}}$	$\frac{\text{Tensile strength}}{(\text{Specific gravity})^2}$
Chrome-vanadium steel	7.85	164,000	20,800	2,700
Structural steel	7.83	65,000	8,300	1,060
Cast iron, gray	7.0	35,000	5,000	720
Titanium alloy	4.7	145,000	31,000	6,600
Aluminum alloy	2.8	56,000	20,000	7,200
Magnesium alloy	1.81	44,000	24,300	13,400
Glass fabric laminate	1.9	45,000	23,600	12,500
Asbestos cloth laminate	1.7	9,000	5,300	3,100
Paper laminate	1.33	20,000	15,000	11,300
Cellulose acetate	1.3	5,000	3,900	3,000
Methylmethacrylate	1.18	8,500	7,200	6,100
Polystyrene	1.06	5,500	5,200	4,900
Polyethylene	0.92	1,300	1,400	1,500
Sitka spruce	0.40	17,000	42,500	106,000

The values given here are average values. Different compositions, heat-treatments, etc., of a given material may differ widely from the values shown here.

corresponding value of the specific gravity, or the square of the specific gravity, or some other power of the specific gravity. The function of specific gravity to be used depends on the type of structure in which the material is used. For example, to select the strongest material to carry an axial tensile load in a rod of given length and given weight, the ultimate strength of various materials should be divided by their specific gravity to obtain comparative values.

On the other hand, if the problem is to select the material for the strongest beam of given length, weight, and *width*, the strength of each material considered should be divided by the square of its specific gravity. The results obtained for these two examples are shown in Table XXXVI for several materials. The data shown in the table indicate that the mechan-

ical properties of some plastics compare favorably with those for some metals when weight is taken into consideration.

It should be noted that no general rule can be laid down for comparing the strength or stiffness of different materials on the basis of equal weight of structure. The requirements for the given application must be considered.

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Questions

1. Describe the characteristics that differentiate plastics from other materials.

2. Define polymer, monomer, polymerization.

3. Name several properties which are characteristic of most plastics and which are desirable properties for a stress-carrying material. Name some undesirable properties of plastics used for a stress-carrying material.

4. What is a thermoplastic? A thermosetting plastic?

5. Name a few structural or machine parts which can be made of a plastic with satisfactory results.

6. Define and state the function of a binder, filler, plasticizer, catalyst.

7. What are the strong points and the weak points of hard rubber for a machine part?

8. Describe at least five methods of molding articles made of a plastic.

9. Consulting the values given in Table XXXV, choose a plastic as the material for making (1) a rowboat, (2) a dress fabric, (3) a "curved ruler" for a draftsman, (4) table dishes, (5) a cabinet with shelves for dishes, (6) false teeth, (7) frame for eyeglasses, (8) washers for water pipes and fittings, (9) electrical insulation. Give a reason for each choice.

10. Name some automotive and airplane parts which may appropriately be made out of plastics. What plastics may be used and why?

11. What are the advantages of canvas-laminated gears as compared with metal gears for certain applications?

12. What factors that are usually unimportant in the testing of metals must be taken into account in the testing of plastics?

13. Which plastics show the greater elongation before fracture, thermoplastics or thermosetting plastics?

14. Do any of the plastics have a yield point? If so, name one.

15. A round rod is ½ in. in diameter and is made of steel having a tensile strength of 75,000 lb. per sq. in. It is to be replaced by a round rod of methylmethacrylate of the highest tensile strength available. What must be the diameter of the methylmethacrylate rod to carry the same tensile load before fracture which the steel rod will carry?

16. Solve a similar problem for a round rod of the weakest plastic listed in Table XXXV.

17. Solve a similar problem for a round rod of the strongest plastic listed in Table XXXV.

CHAPTER XVII

RUBBER, LEATHER, ROPE

Rubber, General Characteristics. The special field of usefulness of rubber as an engineering material depends on four salient characteristics: (1) its value as an electrical insulator, (2) its impermeability to water and gases, (3) its ability to withstand great deformation without serious structural damage, and (4) its ability to absorb energy of shock by mechanical hysteresis. As an electrical insulator rubber is used in very large quantities for insulating covering for electric wires and for insulating bushings and plates. The waterproof and gasproof qualities of rubber make it widely used for hose for water, for compressed air, and for gas, and, together with its ability to withstand great deformation, make it the material universally used for pneumatic tires for vehicles. Its ability to absorb energy makes it useful in members whose function it is to take up shocks in machines and structures, such as buffers.

Production of Rubber. Natural rubber in commercial use is produced from a fluid which exudes from the outer wood of several species of tropical trees and shrubs. The rubber industry is well developed in Central America, the tropical countries of South America (especially Brazil), Ceylon, the Malay Archipelago, the Dutch East Indies, and central Africa.

The fluid from which rubber is made exudes from a special system of ducts in the outer wood of the rubber-producing tree or shrub, and is quite distinct from the ordinary "sap" of the tree. This fluid is known as latex. The latex is gathered in buckets and coagulated into a solid mass by heat, by the addition of chemicals, or by churning. This mass after being "cured" or antisepticized by smoking is the "crude" rubber which is the raw material for the manufacture of rubber goods. The crude rubber is washed and shredded by knives, then mixed with sulfur (and other ingredients varying in accordance with the special service the manufactured rubber is to perform) into a "dough," and this dough is rolled into sheets or pressed into shapes and "vulcanized" by the combined action of heat and pressure. For thin sheets the vulcanizing may be accomplished by treating the crude rubber sheet with a solution of carbon bisulfide. The percentage of sulfur used in vulcanizing determines whether the rubber shall be hard or soft. A high percentage of sulfur gives hard, brittle rubber, and a low percentage gives soft rubber.

For a good grade of soft rubber a combination of 92.5 per cent crude rubber with 7.5 per cent of sulfur is not uncommon.

Synthetic Rubber. At the outbreak of the Second World War the principal source of natural rubber was in the Malay Archipelago and the Dutch East Indies. The Japanese occupation of these islands cut off this supply from America and Europe, and the production of synthetic rubber became a matter of vital importance. Experimentation on raw materials, chemical composition, physical properties, and methods of economical production was started on an immense scale, and the result is that today synthetic rubber is available in large quantity. At least one of the commercial types of synthetic rubber ("neoprene") has excellent heat-resisting and chemical-action-resisting properties. Neoprene is used for gasoline-handling hoses (where rubber would be subject to rapid deterioration) and for many moderately high-temperature applications such as conveyor belts.

The term "synthetic rubber" is really a misnomer. The characteristic molecule of natural rubber, isoprene, has not been artificially produced, but rubberlike substances have been produced in which the characteristic molecule differs but slightly from isoprene. A synthetic rubber may be defined as a material which can be stretched at least 100 per cent and which after such stretching returns to approximately its original length in a short time. Three types of synthetic rubber are designated as "neoprene," "buna," and "butyl." The raw materials from which synthetic rubber is made include petroleum, natural gas, potatoes, grains, sugar, molasses, coal tar, nitrogen (in air), limestone, coke, salt, and sulfuric acid.

Physical Properties of Rubber. Soft rubber stretches from 6 to 10 times its original length without breaking, while hard rubber is almost as brittle as cast iron, although it may be made flexible by heating to moderate temperatures. Frequently heating hard rubber in boiling water makes it flexible; rubber in tension does not have a constant modulus of elasticity. This is illustrated in Fig. 123, in which stress-strain diagrams for three typical rubbers tested in tension are shown. These tensile tests were not carried to fracture. One particularly interesting feature of the stress-strain diagram for soft rubber is the reversal of curvature in the higher stress range. In comparing this stress-strain diagram with a typical stress-strain diagram for steel, it can be seen that rubber when very greatly stretched will exhibit an *increasing* resistance to further strain. A steel specimen will show a *decreasing* resistance to strain as the latter approaches the strain at fracture.

When soft rubber is subjected to a compressive load, a somewhat similar tendency is noted (see Fig. 124). The rate of change of strain

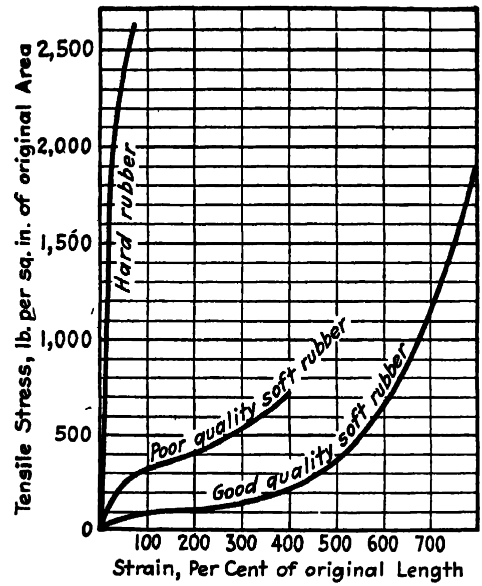

FIG. 123. Stress-strain diagrams for rubber in tension, based on original cross section of specimen.

decreases with increasing stress, thus exhibiting an increased resistance to strain at higher stress levels. This is the opposite of the characteristics of iron and steel.

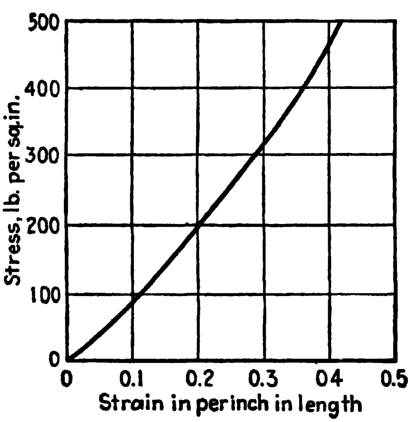

FIG. 124. Stress-strain diagram of soft rubber in compression. Stress based on original cross section of the specimen.

The results of short-time tensile on some typical rubbers are summarized in Table XXXVII. These data give no indication of creep of rubber under long-continued steady loads. With such loads there is probably a decrease of the tensile strength. Since rubber shows no well-defined ultimate strength in compression, a safe working limit may be taken as that stress which will reduce the length of the specimen by one-half.

The great flexibility of soft rubber may tend to make it unsuitable for resisting flexure or torsion without excessive deformation. However, this characteristic is frequently used to advantage in vibration isolaters or other members which will be called on to absorb considerable amounts of energy.

Energy Absorbed by Rubber under Stress. Volume for volume or weight for weight rubber under stress can absorb very much more energy than can steel or any other metal. Taking the sample of good quality soft rubber whose stress-strain diagram is shown in Fig. 123 at a stress of

TABLE XXXVII. MECHANICAL PROPERTIES OF NATURAL RUBBER AND OF SOME SYNTHETIC RUBBERS

Data on natural rubber are taken from the Goodyear "Handbook of Molded and Extruded Rubber," by permission of the Goodyear Tire & Rubber Company, Inc., Akron, Ohio. Data on synthetic rubber are taken from the A.S.T.M. Symposium on Synthetic Rubber, 1944, by permission of the American Society for Testing Materials, Philadelphia.

Material	Tensile strength,[1] lb. per sq. in.	Elongation at fracture, per cent	Modulus of elasticity for small deformations, lb. per sq. in.	Tensile strength at 200°F., per cent of tensile strength at room temp.
Natural rubbers:				
Rubber, sponge	......	...	15	
Rubber, soft	2,500	800	150	
Rubber, resistant to abrasion	3,500	450	500	
Rubber, hard (ebonite)	10,000	6	150,000	
Synthetic rubbers:				
GR-M polychloroprene	3,000	500	......	40
GR-S synthetic rubber sheath	2,500	500	......	33
Buna, type *NLA*	3,000	450	......	33
Thiocol	1,500	600	....	33

[1] The tensile and elongation values were determined under standard A.S.T.M. procedures.

220 lb. per sq. in., the extension is 4 in. per inch original length. The energy required to produce this stretch is approximately

$$0.5 \times 220 \times 4 = 440 \text{ in.-lb. per cu. in. of material}$$

For the sample whose stress-strain diagram in compression is shown in Fig. 124, the energy required to compress the rubber to 60 per cent of its original thickness is approximately 70 in.-lb. per cu. in. of material. These values may be compared with the energy necessary to stress spring steel in tension or compression up to a working stress of 50,000 lb. per sq. in. Taking E for steel as 30,000,000 lb. per sq. in. the strain corresponding to 50,000 lb. per sq. in. is 0.00167 and the energy required to produce this strain $0.5 \times 50{,}000 \times 0.00167 = 41.7$ in.-lb. per cu. in. of material.

For structural steel stressed up to 16,000 lb. per sq. in. the energy required is 4.27 in.-lb. per cu. in. of material. The energy per cubic inch of

material required to produce a safe working stress is a measure of the shock-absorbing capacity of the material, and the figures given in this paragraph show that for tension members, such as pneumatic tires, rubber will absorb about 10 times as much energy per cubic inch as will spring steel. For compression members, such as buffers, rubber, volume for volume, will absorb about 3.75 times as much energy as will spring steel. Furthermore, parts made of rubber must be much larger than parts made of steel for resisting the same loading. The total energy (energy per cubic inch times volume of rubber part) absorbed by rubber parts becomes still greater when compared with the energy absorbed by steel parts.

"Mechanical Hysteresis" of Rubber. In common speech rubber is spoken of as highly elastic. Using the technical definition of elasticity

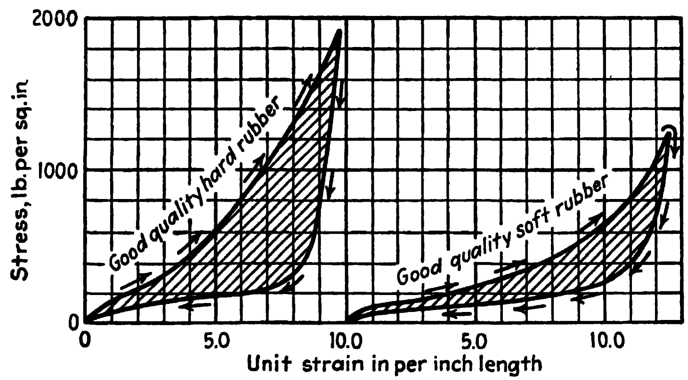

FIG. 125. Stress-strain diagram for rubber subjected to a cycle of stress.

given on page 19 rubber is not perfectly elastic. Moreover, if rubber is subjected to a cycle of stress (see page 52) a considerable amount of the energy required to deform the rubber is lost in mechanical hysteresis. Figure 125 gives stress-strain diagrams for a cycle of stress for two typical samples of rubber. The amount of energy lost in mechanical hysteresis is measured by the shaded area for each diagram. The hysteresis loss is considerable even when the rubber is loaded and unloaded at a slow rate, and it is much larger when rubber is subjected to rapidly applied cycles of stress. The stress-strain diagram for rubber is greatly affected by the speed of loading.

The energy lost in hysteresis in such members as pneumatic tires on automobiles running at high speed is sufficient to produce appreciable heat, which in itself tends to weaken the rubber. The transformation of energy into heat in rubber tires, rubber belting, and other rubber parts subjected to rapid changes of load may play an important part in shorten-

ing the life of such parts. The high mechanical hysteresis of soft rubber makes it the outstanding material for damping vibration and absorbing the energy of rapidly applied loads (shocks).

Deterioration of Rubber. Under the action of air and of light, vulcanized rubber tends to become hard and brittle with the lapse of time. This is illustrated by the gradual loss of stretch in rubber bands left lying on desks for some time. Rubber is little affected by dilute acids, by water, or by dilute alkalies, but is readily "rotted" (rendered brittle) by oils. The deterioration of rubber may be greatly retarded by the use of organic substances related to aniline. Properly compounded and vulcanized natural rubber, as made today, resists deterioration much better than did rubber made in the 1930's. Rubber is inflammable and melts at about 370°F.

Uses of Synthetic Rubbers. Perhaps the greatest advantage the synthetic rubbers have over natural rubber is the high resistance of the synthetic rubbers to the deteriorating action of oils. The various synthetic rubbers all seem to resist the attack of acids and alkalies somewhat better than do most of the organic plastics. Most of the synthetic rubbers seem to retain their elastic properties at temperatures of 150°F. better than do the natural rubbers.

Their resistance to attack by oil makes the synthetic rubbers very useful for gaskets, packings, and diaphragms. Chlorophene synthetic rubber has been especially effective as an absorber of the energy of vibration. Most of these synthetic rubbers have been found useful as electrical insulating materials and for equipment for handling chemicals.

Leather. As an engineering material leather is used in two forms, rawhide and tanned leather. Rawhide is the salted hide of animals, usually ox hide. It is used for gears, for belt lacing, and for some belts, though tanned leather is the usual material for belting. Rawhide is a tough, strong material with little capacity for stretch. Rawhide gears have about the strength of cast-iron gears under steady load, and a higher strength under shock. Rawhide gears operate with very little noise.

Tanned leather is prepared by treating raw hides with a tanning solution prepared from oak bark. Leather is used for belting and for hydraulic packings. Leather suitable for good-quality belting is obtained from the part of hides left after cutting away the belly. Belting is built up by cementing or riveting together strips of tanned leather. Single-ply belting is made from one thickness of leather, two-ply belting from two thicknesses of leather, and so on. Single-ply leather belting is about 0.23 in. thick and two-ply leather belting is about 0.34 in. thick.

Weight and Strength of Leather Belting. Leather weighs about 0.035 lb. per cu. in., its specific gravity being very nearly unity. The

ultimate tensile strength of good-quality leather belting is about 3,600 lb. per sq. in., which corresponds to a strength of about 620 lb. per in. width for single-ply belting and about 1,100 lb. per in. width for two-ply belting. Under a tensile load of 2,250 lb. per sq. in. applied for 1 hr., belting should stretch not more than 13.5 per cent of its original length.

Strength of Belt Joints. If the free ends of a piece of belting are fastened together by chamfering, lapping, and cementing, the strength of the joint can be made nearly equal to that of the leather. Joints in belting are, however, more commonly made by lacing the free ends together with rawhide strips or with wire, or by using some special form of flexible metal connection. The best joints (with the exception of cemented joints) are made by the use of special lacing machines which thread a spiral of steel wire through each free end of the belt. The two spirals are dovetailed together, and a pin of metal or of rawhide is run through the two spirals making a hinge joint.

Ordinary laced joints in belting have about one-third the strength of leather; joints made by the use of special lacing machines may have strength as high as one-half the strength of the leather.

TABLE XXXVIII. ALLOWABLE TENSION ON LEATHER BELTING
Based on values in Table X, page 244, "Machine Design" by Hyland and Kommers, McGraw-Hill Book Company, Inc.

Grade	Average thickness, in.		Allowable tension in belting, lb. per in. width			
	Single ply	Double ply	Single ply, laced	Double ply, laced	Single ply, cemented	Double ply, cemented
Light.......	0.140	0.250	30	60	60	92
Medium....	0.172	0.312	45	87	85	120
Heavy......	0.205	0.372	55	100	95	155

Table XXXVIII shows allowable tensile loads per inch width of belt for leather belts with laced joints and for those with cemented joints.

Canvas Belting, Flat Rubber Belting. Woven canvas belting is made in four-, six-, eight-, and ten-ply thicknesses. It weighs from 0.03 to 0.05 lb. per cu. in., depending on the waterproofing and sizing material used. It is about as strong as leather belting, but has not so much "stretch" or so high a coefficient of friction between itself and the surface of pulleys as leather belting. It is used mainly for agricultural machinery. Flat rubber belting is made on a foundation of woven duck impregnated with rubber. Its special feature is its resistance to moisture, and it is

used for driving machinery in damp locations. Flat rubber belting weighs about 0.045 lb. per cu. in. and has a tensile strength of about 900 lb. per sq. in. Table XXXIX gives allowable tensile loads per inch width.

TABLE XXXIX. ALLOWABLE TENSION ON FLAT "ENDLESS" RUBBER BELTING
Based on values in Table X, page 244, "Machine Design" by Hyland and Kommers, McGraw-Hill Book Company, Inc.

Belting	Pounds per linear inch of width
Four ply	60
Five ply	76
Six ply	90
Seven ply	106
Eight ply	122
Nine ply	138
Ten ply	155

V-belt Drives. Unless there is a fairly high belt tension, a flat belt will slip to an excessive degree. This slip is especially likely to occur in a belt drive in which the flat belt connects a small pulley on one shaft to a large pulley on a shaft close to the first. In order to avoid excessive slip in such a case, it is necessary to have a high belt tension, frequently so high that there is overheating in the belt and in the shaft bearings.

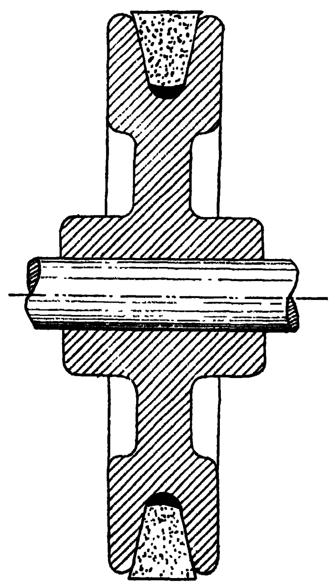

FIG. 126. V belt and pulley.

For such drives, V belts with a trapezoidal cross section and pulleys with V-shaped grooves are widely used. Figure 126 shows such a belt and pulley in cross section. The wedging action of the belt in the V groove of the pulley increases the driving force which may be transmitted without serious slip or overheating and sets up a combination of longitudinal tensile, lateral compressive, and diagonal shearing strains in the V belt.

The V belt is an "endless" belt made up of cotton cords and fabric impregnated with rubber. In addition to the stresses noted, the V belt is subjected to a cycle of bending stress each time it passes around a pulley. V belts and pulleys are made in great numbers by various manufacturers and their strength has been fairly well determined by their behavior in service. The names of four such manu-

facturers are given in the references at the end of this chapter and they can probably supply pamphlets with tables of belt sizes, pulley sizes, and power which can be safely transmitted at various speeds.

Rope. Rope is made by straightening and twisting together the fibers of certain plants, especially the fibers of hemp. It is also made from cotton yarn and there is promise that the fibers of synthetic nylon may be used to make very strong rope. Manila hemp rope has a weight in pounds per foot of about $w = 0.32d^2$, in which d is the diameter of the rope in inches and w the weight in pounds.

The tensile strength of good quality Manila hemp rope, measured in pounds, is as follows: tensile strength $= 5{,}000d(d + 1)$, in which d is the diameter of the rope in inches. This formula is based on tests made by Stang and Strickenberg at the National Bureau of Standards.

For rope made from cotton yarn the equation for weight in pounds per foot is $w = 0.26d^2$; and the equation for tensile strength in pounds is $4{,}600d^2$.

The use of nylon fibers for rope results in a considerably stronger rope than one made of Manila hemp. Such nylon rope possesses nearly perfect elastic action up to a considerable strain. Nylon rope is not subject to rot or to deterioration other than that from water. A typical use of nylon rope is the tow rope for gliders, in which the nearly perfect elasticity and the relatively small weight of the rope are desirable properties.

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Questions

1. Outline the production of natural rubber.

2. What is the difference in composition between natural and synthetic rubbers? Name some of the raw materials used in making synthetic rubber.

3. What property of rubber would be a measure of ability to give good service in the tires of an automobile?

4. Compare rubber with (*a*) structural steel, (*b*) Douglas fir, and (*c*) portland cement concrete with respect to (1) strength, (2) stiffness, (3) elastic resilience, (4) energy required for fracture in tension, and (5) mechanical hysteresis under a stress one-half the tensile strength.

5. How large an oak block would be required to absorb the same amount of energy as would be absorbed by a rubber buffer 6 in. in diameter and 2 in. thick, when the rubber was compressed to a thickness of 1.25 in., allowing a compressive stress of 3,000 lb. per sq. in. in the oak? (Use the stress-strain diagram for soft rubber in compression as given in the text.)

6. What is the outstanding property required for synthetic rubber?

7. What are the advantages of synthetic over natural rubber? What are the advantages of natural over synthetic rubber?

8. Why is a V-belt drive for short distance between driving and driven shafts more efficient than a flat-belt?

9. What kind of belting would you recommend for a small electric motor driving (*a*) a ventilating fan, (*b*) a dynamo from a water wheel, (*c*) a threshing machine, (*d*) a lathe? Give reasons in each case.

10. A manila rope 2 in. in diameter is to be replaced by a chain. What diameter of structural steel round rod would you use to make the links of the chain, so that it could safely lift as great a weight as the Manila rope?

11. In Table XXXVIII, the allowable tension on a medium single-ply leather belt is given as 40 lb. per in. of width. Allowing 3,600 lb. per sq. in. for the tensile strength of leather, and remembering that a laced joint in a leather belt is only about half as strong in tension as the leather belt itself, what is the "factor of safety" for the belt?

CHAPTER XVIII

TESTING AND INSPECTION: EXPERIMENTAL STRESS ANALYSIS

Necessity for Testing. In the first chapters of this textbook, the various forms of failure of engineering materials were outlined and discussed. It was pointed out that a primary obligation of an engineer is to be as sure as he possibly can that the materials which he uses in a machine or a structure will not fail under all possible service conditions which may be expected for that structure or machine. The engineer, then, must have some reliable method of assuring himself that the actual materials which he purchases are of acceptable quality and that they are trustworthy within certain standardized limits of stress and fabrication condition.

Likewise, the producer of commercial engineering materials must have reliable methods for measuring the quality of his products, so that he can be as sure as is possible that each lot of material produced is up to the standards specified for that material. Thus the problem of measuring the quality of materials by performing suitable tests on specimens of the material is a problem which is faced by *both* the producer and the consumer of materials. Frequently the requirements of both producer and consumer can be met by the same set of tests.

Specifications for materials are discussed in Chap. XIX.

The Testing Engineer. As the practice of judging the acceptability of shipments of materials from the results of tests becomes more and more the general rule, the work of the testing engineer who plans and conducts such tests becomes of increasing importance. His service to the public is no small service; he safeguards buildings, bridges, ships, machines, and roads against danger of failure on account of poor material, he makes possible the use of new materials, and widens the field of use of well-known materials. The testing engineer should possess the highest integrity, and should have a clear understanding of the mechanics of materials and of the general properties of known materials. He must be proof not only against any outside influence tending to cause him to report dishonest results, but also against self-deception and prejudgment as to the outcome of tests. Having made tests carefully, he must possess the courage to stand by the results of the tests, whatever those results may be. He should exercise tact and sound judgment in interpreting the

results of tests, and in order that he may do so, he should have a clear understanding of both the content of and the reasons underlying the codes of standards for materials, and the methods of testing used.

Definition of Terms. *Inspection* of materials of construction comprises the examination for surface defects, for correctness of dimensions, for methods of manufacture, etc., and also the making of tests to see whether materials possess the required qualities. *Testing* includes the making of standard tests to determine whether materials possess required qualities, and also the making of special tests of materials to determine properties not thoroughly known. Tests of material comprise chemical analyses, tests of strength, hardness, toughness, and ductility, microscopic and X-ray examination. The statement of requirements as to correctness of dimension, surface finish, strength, chemical ingredients, freedom from defects of structure, etc., forms the *specification* which samples taken from a shipment of that material must "pass."

Commercial Testing. Commercial testing consists, in general, in making tests on selected samples from a shipment of material. It is evident that the proper selection of samples is of very great importance. The samples should be taken from various parts of the shipment, and all samples should be so marked as to make identification easy and certain. Carelessness or lack of thoroughness in sampling is one of the most serious sources of trouble in commercial testing.

On the result of commercial tests depends the acceptance or rejection of large shipments of material, and the tests should be made with a high degree of precision. Commercial testing must also be rapid. The methods and apparatus used should be of the simplest character consistent with accuracy of work.

Chemical tests are very commonly used in commercial testing. In general, chemical tests are made to determine the presence of a sufficient amount of desired ingredient (*e.g.*, carbon in rail steel) or to determine the absence of a dangerous amount of an undesirable ingredient (*e.g.*, sulfuric acid in portland cement or phosphorus in steel). A chemical analysis does not give complete information as to the nature and properties of a material. Two pieces of steel may show the same chemical composition, but in a testing machine may develop widely different strength.

Microscopic examination of the structure of a material is used in connection with commercial tests of materials, especially of metals. Microscopic examination reveals the structure and the texture of the material, and sometimes may be used to detect the presence of flaws. Microscopic tests are used as auxiliary to tests of strength and chemical tests to furnish additional experimental evidence on the structure of the mate-

rial, rather than as the main tests to determine acceptability or nonacceptability.[1]

Physical tests of samples are very commonly used to determine the acceptability or nonacceptability of a shipment of material. The commonest strength test is a tension test to destruction. Such tests are made in some form of testing machine fitted with a mechanism for applying load, usually some form of screw power or a hydraulic press, and with some mechanism for measuring the load applied.

The properties of a material commonly determined in a commercial tension test are (1) some index of elastic strength, usually the yield point or the yield strength (see page 22), (2) the ultimate tensile strength, usually called simply "tensile strength," (3) the elongation of the fractured test specimen over a definite gage length, and (4) the reduction of area of cross section of the zone of fracture. For brittle materials the determination of the yield strength is very rarely made. Figure 127 shows forms of test pieces in common use for strength tests of various materials.

Load tests, not to destruction, are occasionally used to determine the acceptability of car couplers, chain, and some other machine or structural elements and also for completed bridges, and for floors of buildings. In such service tests a load, called a proof load, is applied. This proof load is slightly greater than the working load for the member or structure, and under such test load an examination is made to detect evidence of structural damage, such as undue deformation, flaking off of paint or scale, and cracks.

Impact tests are made on car couplers, rails, and some other members used in railway service. For such tests a known weight is allowed to fall through a given height striking the sample piece to be tested. The acceptability of the shipment is judged by the energy of the blow and the amount of permanent distortion and of cracking developed by the blow.

A testing engineer who is charged with the responsibility of accepting or rejecting a shipment of material will be well advised to follow the standard test procedures[2] specified by the A.S.T.M. These standards should be followed rigorously, especially if there is any possibility of legal action in case the materials seem to be of questionable quality.

[1] Some specifications for metals state the minimum allowable number of crystalline grains per square centimeter to ensure fine-grained metal.

[2] The A.S.T.M. Standards are contained in a set of several volumes, covering practically all engineering materials, metallic and nonmetallic, liquid and solid. A set of standards is published every three years by the American Society for Testing Materials, 1916 Race St., Philadelphia 3, Pa. Individual standards for different materials, and groups of related standards for testing them, are available in pamphlet form.

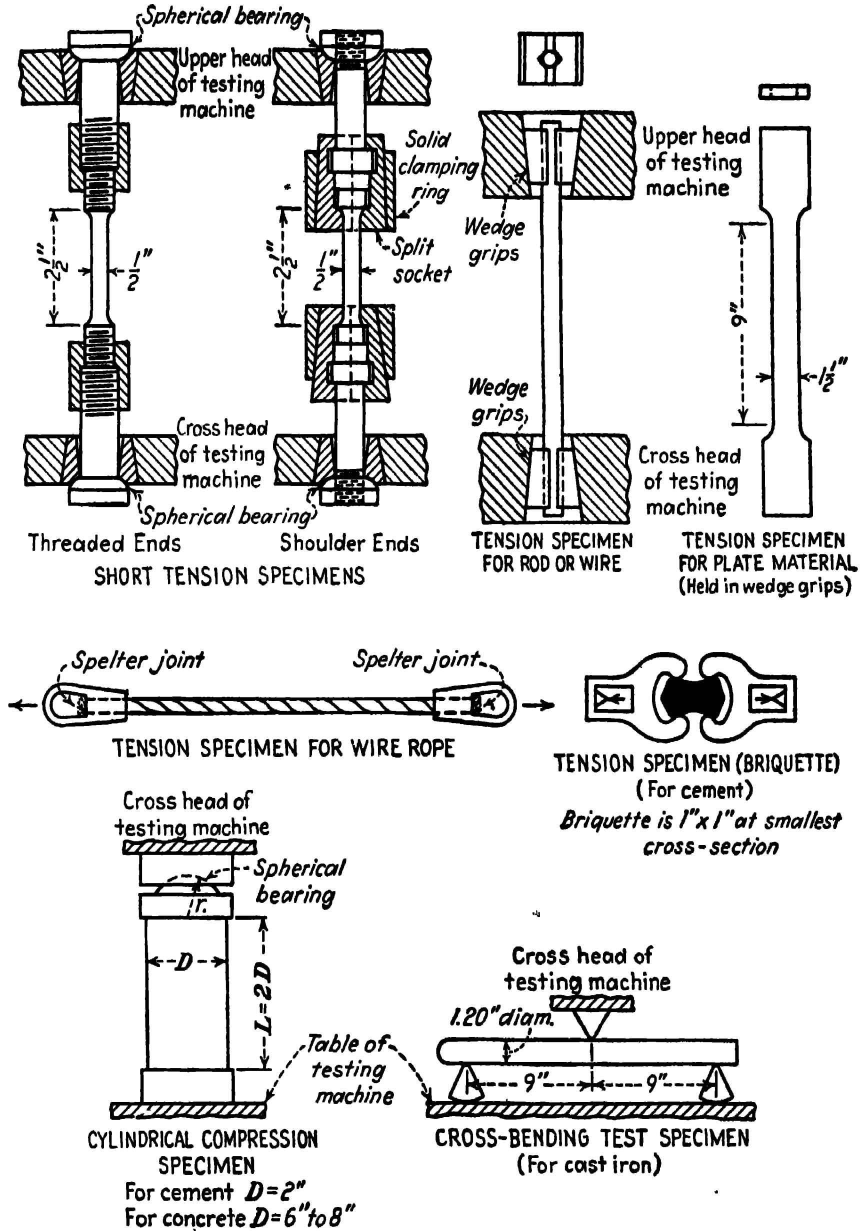

FIG. 127. Various forms of test specimens for strength tests of materials.

When an engineer is called upon to present his conclusions in a court of law, the use of such recognized testing procedures is almost imperative.

Practically all physical tests of engineering materials for strength and ductility consist of first preparing suitable samples or test specimens, measuring the original dimensions of each test specimen, and then one by one subjecting the test specimens to measured external load or moment, observing the resulting effects on the specimen. To do this it is necessary to use some type of loading device, *i.e.*, a *testing machine*, and to measure

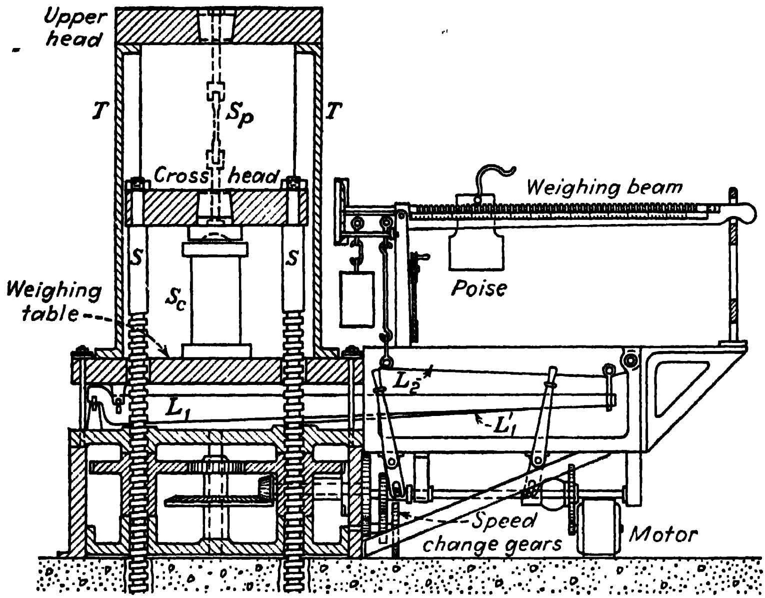

FIG. 128. Screw-power, beam-balance testing machine.

the effects on the specimen by some length-measuring device. Probably the type of testing machine most commonly used is called *the universal testing machine.* This name is given because a universal testing machine may be adapted to making tension, compression, direct shearing, and bending tests. It is not used for torsion tests.

Several manufacturers make universal testing machines and no attempt will be made in this book to give full details of such machines. Suffice it to say that the working principle of all machines for testing material under a single, rather slowly applied, load is the same and that in any such machine there must be (1) a means for holding the specimen in the testing machine (*e.g.*, "grips" for tensile specimens), (2) a means for applying load to the specimen, such as a hydraulic ram or slowly turning screws, and (3) a means for measuring the load applied. If the machine

is of acceptable design, each of these three functions can be performed independently and without mutual interference.

Figure 128 shows in diagram a screw-power testing machine with a balance beam for weighing the load. A large number of beam-balance testing machines are still giving excellent service. However, today most

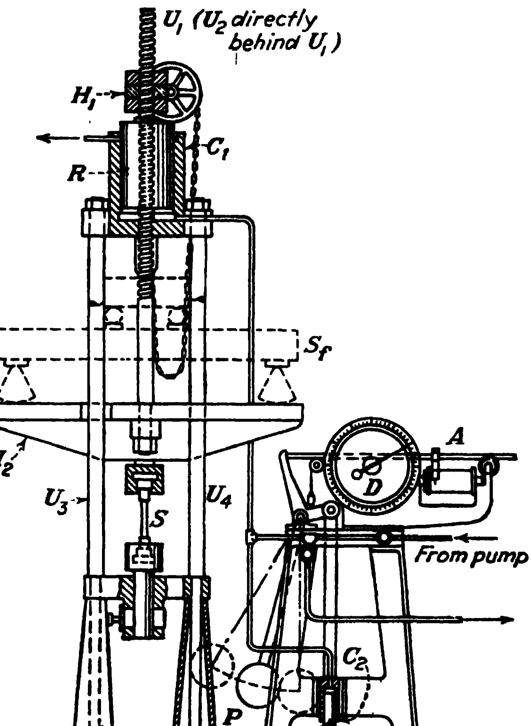

FIG. 129. Testing machine with hydraulic cylinder for applying load and pendulum device for measuring load. The rams R and R_2 are ground and lapped fits in their respective cylinders. No packing is used in either cylinder, so there is a thin film of oil between each ram and its cylinder, and friction of rams in cylinders becomes negligible except for very light loads.

testing machines are equipped with a self-indicating load-measuring device which does not require balancing the weighing beam by hand. Figure 129 shows a testing machine in which load is applied by a hydraulic ram and the load is measured by the motion of a heavy pendulum. Load measurement is self-indicating.

Figure 130 shows a testing machine in which the force is provided by a hydraulic ram and is measured by the reading of a precision pressure

gage N which measures the load by the reading of the pressure in the small hydraulic capsule JK.[1]

Torsion Testing Machines. For testing the shearing strength of material the torsion test is the most suitable, because that test produces shearing stress in a round specimen. Torsion tests cannot readily be made on a tension-compression-flexure testing machine such as is shown in Figs. 128 to 130 and a special form of testing machine is used; Fig. 131 shows one form of torsion testing machine.

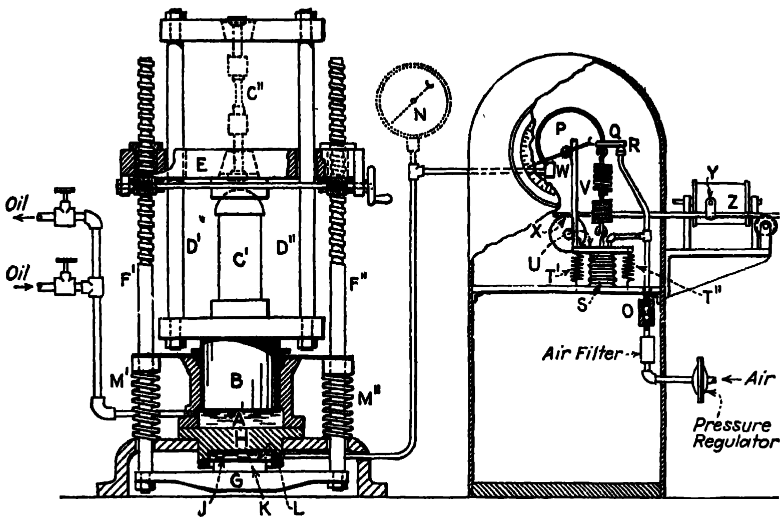

FIG. 130. Hydraulic-power testing machine with hydraulic support for measuring load.

Power is applied by hand through the crank K (or through a drive pulley) and then through the worm M and gear G to turn the chuck C. The specimen S is fastened in two similar chucks one at each end of the specimen, by means of centering jaws J. As the specimen is twisted it swings the heavy pendulum P out toward the position P', and the amount of twisting moment exerted by and transmitted through the specimen is equal to Wa; W is the weight of the pendulum and a is the horizontal motion of its center of gravity. Attached to the pendulum is a finger T which shoves an indicator along a scale E. The amount of motion of the indicator over the scale (a') is proportional to a, the horizontal motion of the center of gravity of the pendulum. Hence the scale E can be graduated to read directly the amount of twisting moment on the specimen.

[1] The device to the right hand of the pressure gage N in Fig. 130 is a recording pressure gage, which is very convenient for recording stress-strain diagrams, but which is not essential for accurate testing.

Torsion test specimens are practically always circular in cross section, either solid or hollow. In addition to type shown in Fig. 131, torsion testing machines are built in which the twisting moment is weighed by the use of a compound-lever system and a weighing scale or a lever resting on a hydraulic support.

The Calibration of Testing Machines. The accuracy of the load readings of a testing machine can be determined by measuring the deflection under load of an elastic proving ring, such as is shown in Fig. 132. The proving ring shown is adapted for use either in tension or under com-

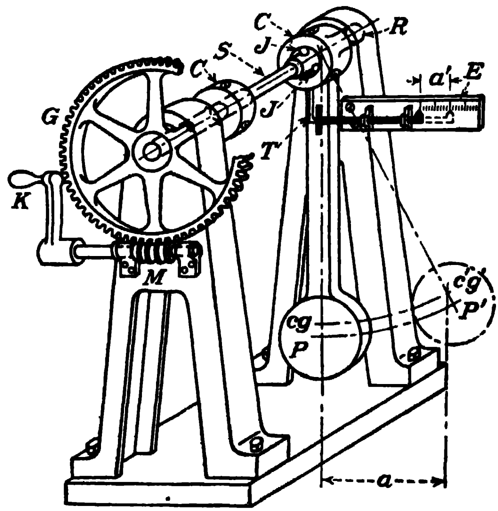

FIG. 131. Testing machine for torsion tests.

pression, provided the maximum load applied to it does not produce a permanent deformation of the ring which can be detected by a micrometer sensitive to, say, 0.0002 in.

The proving ring itself is calibrated by known dead weights. The National Bureau of Standards in Washington has a calibrating ring for this purpose, and standardized weights aggregating 110,000 lb. are available. A ratio can be determined between the load applied by dead weights and the deflection of the ring as measured by the micrometer *M* as it touches the end of the reed *V* (which is vibrated as readings are taken) for a number of loads within the range of the allowable load on the proving ring, and a load-deflection chart can be furnished with the calibrated ring.

From this chart the errors of the load reading of the testing machine can be determined by taking a series of readings up to the maximum capacity of the testing machine, or the maximum safe load on the proving

ring, whichever is smaller. Errors in the load readings of a testing machine can be diminished by adjusting the weight of the poise of a balance-beam machine (see Fig. 128), the weight of the pendulum (see Fig. 129), or the scale of the hydraulic pressure gage (see Fig. 130).

In the specifications of the A.S.T.M. there is no blanket acceptance or rejection of a testing machine on the basis of its accuracy. Instead there is required a statement of the range of loads within which the error of any load reading is not more than 1 per cent. This range is called the *loading*

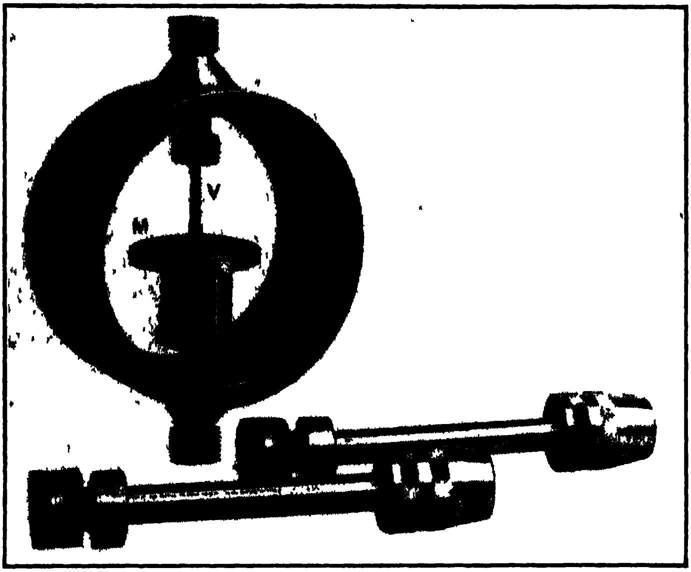

FIG. 132. Elastic proving ring for calibrating the load-weighing scale of a testing machine. The proving ring can be used under a compressive load or, by means of the attachments shown, it can be used under a tensile load. (*Courtesy of Morehouse Machine Co., York, Pa.*)

range for the machine, which should not be used for loads above or below the loading range.

Observations and Measurements. As mentioned before, while a test specimen is being subjected to an external load in a testing machine, the *effects* of that load on the specimen should be observed. Now this process of observation may range all the way from an occasional glance to see if the specimen has been fractured or badly distorted, to a very fine measurement of the distortion (strain) within the specimen, such a measurement as is made when a stress-strain diagram is to be drawn, or when it is desired to determine experimentally locations of stress-concentration or small areas where there is danger of failure of the specimen.

The term "measurement" suggests quantitative determinations rather

than qualitative observations. A consideration of the act of "making a measurement" leads us to see that *almost all* of our laboratory measurements are measurements of *length.*[1] For example, temperature is measured by the length of a mercury column; time is measured by the length of travel of a hand over a curved stop-watch scale. To measure electrical voltage or current, the *length* of travel of a meter hand or the height of movement of a cathode ray is measured.

The observer depends almost entirely upon the sense of sight to convey the impression of a quantitative measurement to the observer's brain. The human eye can perceive only changes in length, color, and light intensity, and so, if some change is to be transmitted to the observer's brain for interpretation into what will be a measurement, that change must be in length, color, or light intensity. The most reliable results seem to be obtained when changes in *length* are measured. The only changes which can be directly measured on a specimen are changes in conformation, that is, *strains* that are quantitatively measured by changes in lengths.

Experimental Stress Analysis. Since it is not possible to measure stress directly at a localized region in a member, but it *is* possible to measure *strain changes,* any experimental evaluations of *stress* at any localized region are best deduced from actual strain measurements. This is not too difficult as long as the ratio of stress to strain remains reasonably constant, for instance below the yield strength of the material as determined by using an "offset" of, say, 0.05 per cent (see Chap. III, Fig. 11, and accompanying text). However, when multidirectional stresses are present, or when stress is not directly proportional to any one *strain,* the analysis of strain readings becomes much more difficult.

Experimental stress analysis (or possibly it should be experimental *strain* analysis) depends on the use of strain-measuring instruments, of which a wide variety are available. Strainometers, or strain gages, as they are sometimes called, fall into two classes: (1) strain gages which can be fastened to and unfastened from the specimen and (2) strain gages which are permanently fastened to the surface of the specimen and which cannot be removed and used on another specimen.

Four strain gages of the first type are shown in Fig. 133. In Fig. 133(*a*) the strain is measured by two symmetrically placed screw micrometers. The average of the strain shown by the two micrometers is the average longitudinal strain (stretch or compression) in the specimen.

Figure 133(*b*) shows a microscope so mounted as to measure the

[1] A possible exception is the balancing with standard weights when we weigh a body, and even in this case if we read the "swing of the pointer" for getting the last significant figure for the measurement of weight, we measure the *length* of the swing.

average strain in the specimen. The magnitude of the strain is measured on a glass scale in the eyepiece of the microscope.

Figure 133(*c*) shows a strain gage in which the measuring unit is a micrometer dial gage which magnifies small motions by means of clock-

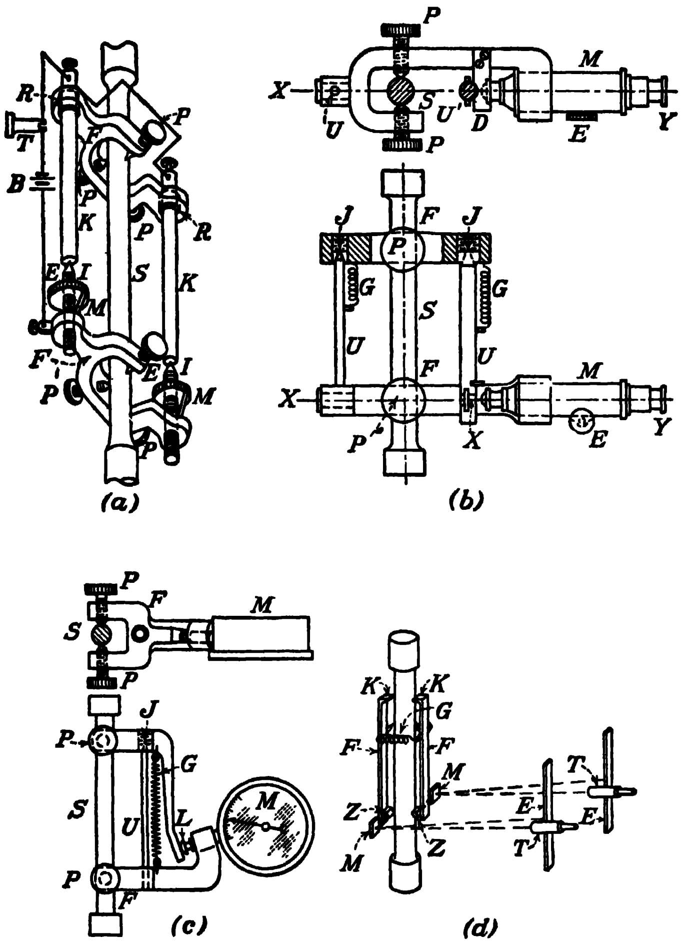

FIG. 133. Various types of mechanical and optical extensometers (or strain gages).

work gears. The strain gage as shown measures average longitudinal strain of specimen directly. It is very convenient to use but not quite so accurate as the other types shown in Fig. 133.

Figure 133(*d*) shows a strain gage in which the measurement is made by the use of an "optical lever." As longitudinal stretch or compression takes place, the small steel "lozenges" *ZZ* rotate through very small

angles and with them move the mirrors MM. The motion of the mirrors is magnified by means of the telescope TT and scales EE. This type of strain gage is very sensitive but rather tedious to set up and adjust.

Wire-bonded Strain Gage. Figure 134 shows a type of nonremovable strain gage which has come into very wide use in recent years. A number

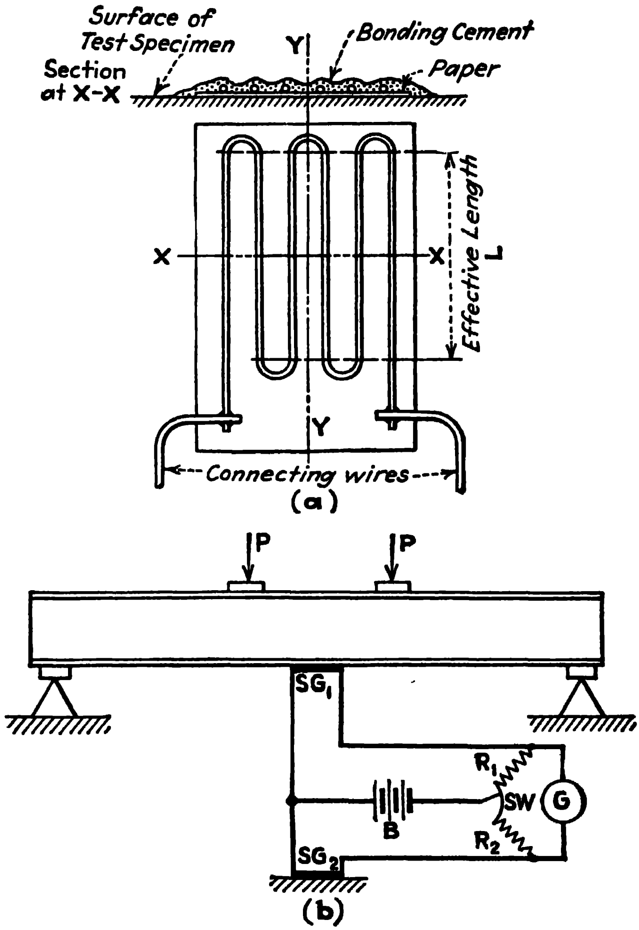

FIG. 134. Diagram of wire-bonded strain gage.

of loops of wire with a high electrical resistance are placed on a paper, then these loops are bonded to the location on the surface of a specimen, or structural part, at which it is desired to measure a strain. Plastic cement is used for the bonding process. The surface of the specimen or part must be carefully cleaned from dirt and scale before the cement is applied. As the specimen or part is stressed, the deformation in the

direction of the loops [YY in Fig. 134(a)] is transferred to the wire, increasing its length and decreasing its cross section under tension, or decreasing its length and increasing its cross section under compression. These changes, especially that in cross section, alter the electrical resistance of the loops of wire.

Figure 134(b) shows the application of a wire-bonded strain gage to the measurement of strain in the flange of an I beam. The gage SG_1 measures the longitudinal strain plus or minus any deformation due to change of temperature. The auxiliary strain gage SG_2 is placed near the beam and rests on a piece of metal similar to that in the beam, or better, on an unstressed end of the beam. The gage SG_2 measures the deformation due to change of temperature. By these two gages a correction for temperature effect can be made in the reading of SG_1.

The connecting wires from the wire-bonded gages lead to a Wheatstone bridge with battery (or other source of electric current) B, resistances R_1 and R_2, a slide wire SW for fine adjustments, and a galvanometer or oscillograph G.

By the use of a delicate galvanometer or millivoltmeter very small strains can be measured and, if desired, the sensitivity can be increased by vacuum-tube amplifiers. A single wire-bonded unit is inexpensive, but it can be used on only one specimen or structural piece. Attempts to remove a wire-bonded strain gage from one specimen and then use it on another have so far met with very little success. The wire-bonded units are made by the thousand, and from each lot made a number of units are selected and calibrated by taking their readings on a specimen subjected to a series of known strains. The results of these calibrating tests are then examined and, if they are in close agreement with each other, the average results serve as a basis for a formula of the gages in that particular lot— a formula or diagram showing the relation between change of electrical resistance and strain in the direction of the lengths of the loops [along axis YY in Fig. 134(a)]. Then the relation between the change of electrical resistance and the galvanometer reading for the Wheatstone bridge used is determined, or known from previous determinations, and the strain can be read directly from a chart or determined directly from a formula. If it is desired to measure strain in more than one direction, additional wire-bonded units must be used.

The wire-bonded strain gage has several limitations. Strains in the direction XX in Fig. 134(a) affect the resistance of the wire by changes set up in the curved part of the loop. The method of calibration of sample gages, which cannot be used again, does not seem so reliable as the calibration of each strain-measuring unit, as is possible with the mechanical strain-measuring devices. Probably with carcful bonding and good

test conditions the error of a wire-bonded strain gage may be not higher than 2 or 3 per cent; it may be much higher with careless handling.

The great advantage of the wire-bonded strain gage is that it can be used in scores of test locations where no other gage is practicable; *e.g.*, in measuring strains in an airplane wing while in actual flight. Then too it can be used over gage lengths as short as $\frac{1}{16}$ in. When the galvanometer G is replaced by an oscillograph, strains can be measured on machine parts in motion. The wire-bonded strain gage has increased the field of possible strain measurements very greatly, and its use will probably become even more widespread in the future.

Other Types of Strainometer. Various other forms of extensometer are in use, but the above samples are believed to be typical. Compressometers, deflectometers, and torsion indicators with similar measuring units are used in compression tests, flexure tests, and torsion tests. They will not be taken up in detail here.

Impact Tests and Testing Machines. Figure 135 gives characteristic stress-strain diagrams for several materials. The maximum ordinate

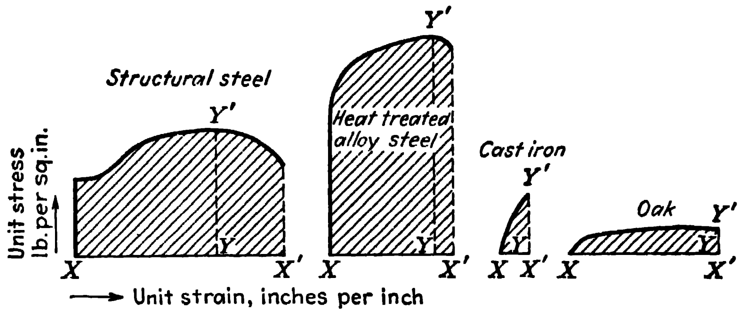

FIG. 135. Stress-strain diagrams for various materials.

YY' of a stress-strain diagram measures the ultimate *strength* of the material, the maximum abscissa XX' measures the ductility of the material, while the area under the whole stress-strain diagram (shown shaded in Fig. 135) measures the combination of strength and ductility defined on page 3 as *toughness*. The ordinates of stress-strain diagrams are measured in *pounds per square inch*, the abscissas are measured in *inches per inch length*, and the area under the diagram is measured in *inch-pounds (or foot-pounds) per cubic inch.*

Another way of determining toughness would be to fracture the specimen by a single blow from a moving mass of metal, measuring the velocity of the mass before and after striking the specimen, and from the loss of velocity determining the energy absorbed in fracturing the specimen, per cubic inch of its volume. This test has been used by some engineers in special cases for tension test specimens of metals. When tests are

made by fracturing a specimen by a single blow, no direct comparison can be made between the results of any of the single-blow impact-testing machines and the ultimate tensile strength or the yield strength shown by an ordinary test in any of the force-measuring testing machines, as are shown in diagram in Figs. 128 to 130.

The impact test measures *energy* required for fracture, not force. Figure 135 shows stress-strain diagrams, complete to fracture, for ordinary tensile tests of structural steel, a heat-treated alloy steel, cast iron, and oak. The ordinates of the stress-strain diagrams give the stresses and the abscissas give the deformations; the areas under the diagrams give

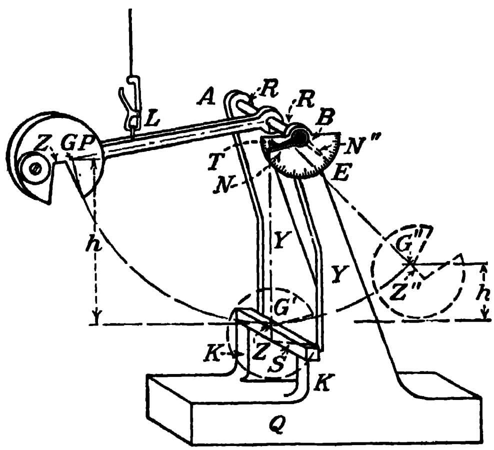

FIG. 136. Simple-beam (Charpy) impact-testing machine.

the energy per cubic inch required for fracture. It will be seen that structural steel shows a lower tensile strength (pounds per square inch) for fracture than the heat-treated alloy steel, but a *higher* energy for fracture (inch-pounds per cubic inch).

The energy required to break a specimen may also be obtained by using a specimen in which a heavy pendulum swings against a flexure specimen and fractures it. Such a testing machine is the Charpy impact tester. Figure 136 shows a Charpy impact-testing machine. A heavy pendulum *P* is hung in ball bearings *R* and counterweighted so that its center of percussion[1] is at *Z*, and its center of gravity at *G*. To its axis is attached an arm *T*, which, as the pendulum swings to the right, pushes an indicating finger *N* around the scale *E*. The finger *N* does not swing back with the pendulum, but remains at its point of highest swing to the right, *N″*. The specimen *S* is supported so that it bears against supports *K*,

[1] For the method of locating the center of percussion of a pendulum see any standard textbook on engineering mechanics.

and as the pendulum falls the specimen is struck by the center of percussion of the pendulum. To make a test the specimen S is placed in position, the pendulum P raised to the position shown by the solid lines, held there by the latch L, and the initial angle of the pendulum read by means of the pointer N; the latch is released, the pendulum falls, strikes the specimen S, fractures it, and then the pendulum rises to some final position G'': this position is determined by reading the final position of the pointer at N''. The energy utilized in fracturing the specimen is equal to $Wh - Wh''$, in which W is the weight of the pendulum, h is the

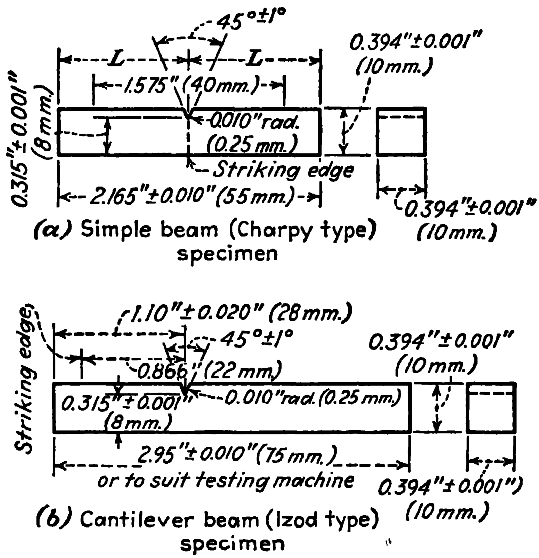

FIG. 137. Notched-bar impact specimens.

vertical fall of its center of gravity, and h'' is the vertical rise of its center of gravity after rupturing the specimen. The initial reading and the final reading of the pointer N give measures respectively of the fall and the rise of the center of gravity of the pendulum. Figure 137(a) shows a Charpy notched specimen.

Another impact-testing machine in wide use is the Izod machine. It is similar in principle to the Charpy machine, but it tests a notched flexure specimen which acts as a cantilever beam rather than a simple beam, as is the case with the Charpy specimen. The Izod specimen is shown in Fig. 137(b).

Significance of Notched-bar Impact Tests. The energy required to fracture a notched-bar impact specimen seems to be an index of a rather indeterminate combination of toughness and sensitivity to localized stress at notches or other "stress raisers." The results of such tests have proved

useful in detecting the use of improper heat-treatment of steel. Notched-bar impact tests have proven useful in acceptance testing of electrical insulating materials, steel for automobile and airplane engine parts, metal for gears, for "live" axles, for turbine blading, and wood for airplane parts.

The results of notched-bar impact tests have not been correlated with the results of ordinary "static" tests or with the results of fatigue tests. Notched-bar impact tests must be made on specimens of a definite standard size, and it has not been found possible to compare test results obtained by the use of different sized test specimens, or by the use of different types or sizes of impact machine.

Hardness Tests of Metals. Various forms of test have been used to determine the somewhat indefinite property called "hardness." For brittle metals, some form of scratch test has been used. A diamond point is pressed against the surface of the metal by a known weight or other force, and the width of scratch made as the diamond point is drawn along is measured with a microscope. This test gives rather variable results, but has proved useful in measuring the variation of hardness in the different crystalline grains of the metal tested.

In general, the hardness tests in most common use today give measures of the resistance of a metal to penetration. Most hardness tests are made by forcing a hardened steel ball, or a diamond point of definite shape, into the surface of the metal under test. The result of a hardness test is generally expressed as a "hardness number" which is determined by the depth or the surface area of the indentation made by a given load.

The Brinell test is the commonest hardness test made, and the "Brinell hardness number" is obtained by dividing the applied load by the area of the spherical impression made by a steel ball 10 mm. in diameter under a load of 3,000 kg. for most structural materials and of 500 kg. for the softer metals. The area of the indentation may be determined from the diameter of the impression after the load has been removed.

Brinell tests are usually made on a special machine using hydraulic pressure. However, they may be made on any small universal testing machine. Tables of Brinell hardness numbers for various measured diameters of indentation are furnished with the machine.

The Rockwell test is similar in principle to the Brinell, but in place of a steel ball 10 mm. in diameter, a steel ball $\frac{1}{16}$ in. in diameter ("B" tests) or a conical diamond point ("C" tests) is used. The depth of indentation under a specified load determines the "Rockwell hardness number." The exact procedure in making a Rockwell test is given with instructions furnished with the testing machine. Various special indentation points and special loadings are used for special Rockwell tests. There is a fairly well-defined relation between Brinell numbers and Rockwell

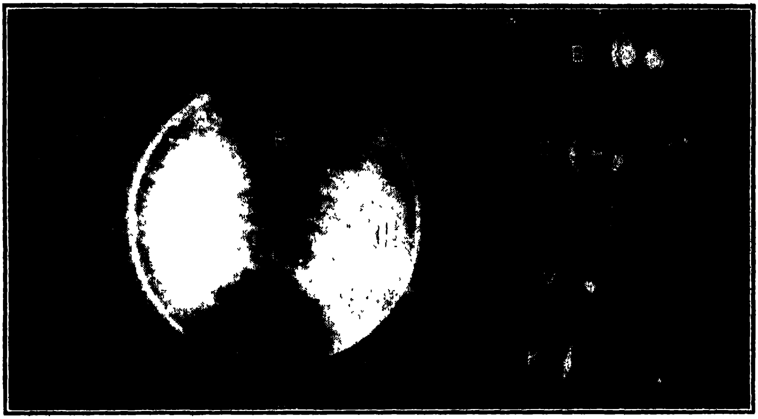

FIG. 138. Hardness-measuring indentations in five different hardness tests. Magnification 7.5 times. The tests were made on a bar of cold-drawn steel with a Brinell hardness number of 121.

Br shows the indentation in a Brinell test by a steel ball 10 mm. in diameter, under a load of 3,000 kg. The diameter of the indentation was measured, and from this the area of the surface of the indentation computed. The Brinell hardness number (BHN) is equal to the load divided by this area of surface. Tables for the direct determination of BHN from diameter of impression are usually furnished with a Brinell hardness tester.

B shows the indentation made by a steel ball $\frac{1}{16}$ in. in diameter under an initial load of 10 kg., followed by setting the scale of the dial on the machine to zero and then adding 100 kg. This is the Rockwell "B" test. The Rockwell "B" hardness number depends on the depth of indentation and is indicated directly on the dial of the tester.

C shows the indentation made by a cone with a diamond point. An initial load of 10 kg. is applied and the scale set to zero as in the "B" test; an additional load of 150 kg. is then applied and the "C" hardness number read off the scale. Various other special "Rockwell" tests are made.

V is the indentation made by a diamond whose penetrating "point" has been ground to the shape of a four-sided "square" pyramid. In this particular test the load was 5 kg. This is the "Vickers" test, but the determination of hardness numbers has not yet been standardized.

K is the indentation made by a diamond whose penetrating "point" was ground to a four-sided pyramid, one of whose diagonals was much longer than the other. In this particular test the load was 5 kg. This is the Knoop test. The Vickers test and the Knoop test have not yet been standardized, but they have promise, especially for hardness on surfaces which would be injured by the indentation of Brinell or even of Rockwell tests.

numbers, and conversion tables are given in Part 1 of the 1949 Standards of the A.S.T.M., pages 1326 to 1328.

A recent hardness tester is the Tukon, in which the indenting tool is (1) a quadrangular diamond pyramid (Vickers indenting tool) or (2) a thin diamond (Knoop indenting tool) which makes a relatively long and narrow indentation. Figure 138 shows the relative sizes and shapes of indentations for Brinell, Rockwell "C," Vickers, and Knoop tests.

A quite different hardness test is the scleroscope test, now rather rarely used. Scleroscope tests give less uniform results than do indentation tests but they can be used on full-sized structural and machine parts, and they are useful when the metal tested is so hard that the indentation is very small. In the scleroscope test, a small weight fitted with a diamond point is dropped from a standard height to the surface of the material under test. The height of rebound, read from a scale on the tube down which the weight falls, gives an arbitrary scleroscope hardness number for the material.

The hardness numbers given by the various hardness test results seem to show some correlation between the various numbers obtained by different tests, and indentation hardness numbers usually give a rough idea of the tensile strength of a metal, although the quantitative relation between hardness number and tensile strength varies for different metals.

Hardness tests may be made without appreciably injuring the strength of the metal tested, unless the structural or machine part is subjected to repeated stress, and the indentations are located in regions of high stress. Under such conditions an indentation might be a dangerous "stress raiser."

Testing Machines for Creep Tests. In the case of the softer metals a suitable testing machine for creep tests consists of dead weights hung directly on the test specimens. For the stronger metals it is customary to use dead weights hung at the end of levers, and the range of motion of the levers must be sufficient to allow 20 to 30 per cent stretch of the specimen. To control the temperature, a furnace around the specimen is necessary.

Figure 139 shows in diagram such a testing machine. The specimen S is fastened to the holders H_1 and H_2 and the upper holder is attached to the "short" end of the lever L. Standard weights are hung on the "long" end of the lever. The specimen is heated by the electric furnace F, and the temperature of the specimen is measured by the current from a thermocouple C held snugly against the specimen. The wires from the thermocouple lead to a millivoltmeter or a potentiometer which indicates the voltage of the thermocouple and hence the temperature of the specimen. In long-time tests a controlling potentiometer is commonly used, cutting down the heating current when the temperature rises a small amount above the desired value and increasing the current when the temperature falls too low. An extensometer M measures the creep of the specimen S.[1]

[1] As shown, the extensometer measures creep in specimen, in grips, and in the bearing of screw threads in nuts. A better arrangement would be to use an extensometer attached directly to the specimen, as shown in Fig. 133*a*, *b*, *c*, and *d*, with projecting rods to operate micrometer dial gages.

Cold-bend Tests. A common shop test for ductility in a metal is the cold-bend test, which is made by bending a sample strip of the metal to be tested round a mandrel of given diameter, and noting the angle of bending when the convex surface of the metal first shows a crack. This test is usually made in a shop by hammering the sample round the mandrel, or by bending in a vise or a hydraulic press. Special testing machines have been devised for making cold-bend tests quickly and easily.

A recently proposed refinement of the cold-bend test consists in laying off a short gage length on the convex side of the bend specimen, bending until a crack appears, then measuring the elongation of the gage length, using a tape or a flexible scale.

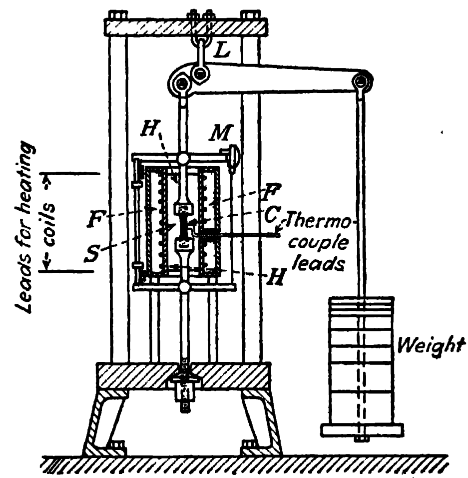

FIG. 139. Testing machine for creep tests at elevated temperatures.

Magnetic Tests of Steel and X-ray Tests of Metals. There seems to be a fairly definite relation between the magnetic properties of steel and its strength properties. This relation has not been developed so fully as to make possible standardized magnetic tests to indicate strength properties, but such tests are a possibility of the future. A magnetic test would be a very useful nondestructive test for finished parts. Magnetic tests for homogeneity, as shown by constancy of magnetic properties over the different parts of a piece, have been used in connection with steel rails, gun barrels, and steam turbine disk wheels.

The direct detection of internal flaws in metal parts by the use of powerful X-ray apparatus has come into quite common use, especially in connection with large castings and welded joints. Steel up to 4 in. thick has been successfully examined in this way, which is the same in principle as the familiar X-ray examination of teeth by a dentist. The X-ray apparatus for steel is extremely powerful, and great care must

be taken to surround the specimen and X-ray tube with thick lead walls to prevent injury to workmen in the same or adjacent rooms.

X-ray photographs of metals as made at the present time cannot be magnified. An X-ray examination or photograph can detect no crack so small as to be invisible if the crack were at the surface. The electron microscope gives promise of detection of very minute cracks (see Figs. 27 and 28).

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7. Baldwin-Southwark Corporation, Philadelphia, Pa. Issues trade publications describing testing machines, and bonded wire (SR-4) strain gages.
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9. Riehle Testing Machine Div., American Machines and Metals, East Moline, Ill. Issues trade publications describing testing machines.
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11. Krouse Testing Machine Co., Columbus, Ohio. Issues trade publications, especially about fatigue testing machines.
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Questions

1. Distinguish between the terms inspection and testing as applied to materials.

2. Discuss briefly the importance of careful sampling of materials which are to be tested.

3. Give illustrations of chemical tests used commercially in testing materials; of microscopic tests; of tests of strength; of tests of ductility; of tests of hardness; of other tests.

4. What is a universal testing machine?

5. Describe briefly the mechanism for applying load, and for measuring force in three common types of testing machine. What are the advantages and disadvantages of each type?

6. Describe a testing machine for determining the shearing strength and stiffness of materials.

7. Describe briefly five types of strain-measuring apparatus for very small strain. What are the advantages and disadvantages of each type?

8. Be able to draw a diagram of a wire-bonded strain gage. What are the advantages and the limitations of such a gage as compared with those of the mechanical strain gages shown in Fig. 133? For determining the yield strength in a tension test specimen, would you use a wire-bonded strain gage or a mechanical extensometer? Which would you use for determining modulus of elasticity of a metal? Which for determining strains in a number of locations in a full-sized structural or machine part? Give your reasons in each case.

9. If you were to make a tension test of structural steel what form of specimen would you use if the material were supplied: (*a*) as a 1-in. diameter round rod several feet long, (*b*) as a flat bar 2 by $\frac{1}{4}$ in. and several feet long, (*c*) as a piece of a billet 4 in. square and 10 in. long? Give reasons in each case.

10. If you broke a cast-iron test bar in flexure (as shown in the lower right-hand corner of Fig. 127) and then machined a tensile specimen from one-half of the broken piece and pulled it in a tensile test would you expect to get the same ultimate stress value in each case? Explain.

11. In the compression specimen shown in the lower left-hand part of Fig. 127, the center of curvature of the spherical seat is shown to lie at the bearing surface between test specimen and face of spherical block. Is it important that the center of the spherical seat should lie in this plane? Explain.

12. How many types of strain-measuring apparatus have you used in your laboratory work in strength of materials? Tell the advantages and disadvantages of each type, as judged by your own experience.

13. Devise a strain-measuring apparatus to measure compressive strain over a 1-in. gage length on specimens ranging in diameter from $\frac{1}{2}$ in. to 1 in. Make the instrument capable of showing a strain as small as 0.0002 in. per inch of gage length.

14. In what units are the results of an impact test usually given? Describe the Charpy impact machine.

15. For Charpy tests of steel why are *notched* specimens used?

16. Discuss the meaning of Charpy tests results.

17. What is the difference between Charpy tests and Izod tests?

18. If you wished to make a test on an ordinary testing machine to give results which could be compared with the results of Charpy impact tests, how would you go about it? Would you need a large testing machine or a small one? What test data would you have to take? In what units would your results be given?

19. Name some machine parts for which the Charpy, or the Izod notched-bar test has been found to distinguish between satisfactory and unsatisfactory material. What is the significance of results of impact tests on notched-bar specimens?

20. Why are not impact tension tests as commonly made as impact flexure tests?

21. Describe the rotating-beam machine for repeated-stress tests. What range of stress does it set up? What kind of stress? What are its advantages and dis-

advantages as compared with a vibratory testing machine? What is the significant result of a series of rotating-beam tests? Why must several specimens be tested to get this significant result?

22. Describe briefly the Brinell, Rockwell, Vickers, Knoop, and scleroscope hardness tests. What advantage have they over tension tests of samples? What physical properties of a material can be estimated from a hardness test?

23. State very briefly the results obtained by cold-bend tests, by magnetic tests, and by X-ray examination of materials.

24. In a testing machine to measure creep under prolonged steady load what precautions would have to be taken during the test which do not have to be taken in an ordinary tension test?

25. What are the advantages and limitations of the direct tension-compression (push-pull) fatigue testing machine? Which of the fatigue testing machines shown in Fig. 31 give the *stresses* set up in the specimen? Which machines measure the deflections or the strains set up? If a strain-measuring type of fatigue testing machine is used and the stresses determined from the strains, is the error serious (1) if the strains are below those at the yield strength of the metal? (2) If the strains are above the yield strength of the metal?

CHAPTER XIX

SPECIFICATIONS FOR MATERIALS

General Characteristics of Specifications for Materials. The codified statement of the requirement for acceptability of a material of construction makes up a set of *specifications* for that material. The content of a set of specifications for a material may be divided into four subdivisions: (1) specifications relating to methods of manufacture to be used, (2) specifications relating to finish, form, and dimensions of the pieces of material in a shipment, (3) specifications for the chemical and physical properties of the material, and (4) specifications for the methods of testing and inspection to be used.

Illustrations of the first subdivision are the requirement that structural steel for bridges shall be made by the open-hearth process and the requirement that stay-bolt iron shall be wrought iron, *not* steel. The second subdivision is illustrated by the statement of allowable variation of actual dimensions of naval brass rod from the nominal dimensions. The third subdivision is illustrated by the statement of maximum allowable sulfur content and for the transverse strength of automotive-gray iron castings. The fourth subdivision is illustrated in the specifications for portland cement in which methods of testing are set forth in detail.

Specifications are never perfect. They are not drawn up for ideal material, but for material which it is possible to obtain at a reasonable cost under existing conditions of manufacture. From time to time it becomes necessary to change details of any standard set of specifications, and, in general, the requirements for acceptable material tend to become more and more exacting as the methods of commercial production are improved.

American Society for Testing Materials. The A.S.T.M. was organized in 1898 and formally incorporated in 1902. Its purpose was stated in the following words: "*The promotion of knowledge of the materials of engineering and the standardization of specifications and the methods of testing.*" Nearly all the remaining paragraphs of this chapter are taken from publications of the A.S.T.M.

The A.S.T.M. was organized as a national society by men who recognized the inadequacy of the language of normal intercourse as a medium for describing or specifying materials for the exacting requirements of science, industry, and engineering.

The stated requirement that an object shall be strong, durable, smooth, and true to dimension, conveys a general picture but the clause is meaningless to an engineer, and is unenforceable until measurable limits have been set for each descriptive term. Strength and durability are general properties, their values varying with the conditions of the test or type of exposure. No mechanically finished surface is smooth and no dimension is exact.

When one endeavors to assign reasonable numerical limits to desired properties he is confronted with a lack of the background information for doing so. If the limits he sets are more exacting than the use requires, he is needlessly increasing difficulty and cost of manufacture; if they are less exacting, he is introducing hazards. To secure the backlog of necessary information, he must resort to experiment, and a great amount of research in materials is published each year in the *Proceedings* of the Society.

Assuming then that one has secured the necessary research data and has prepared an enforceable specification, how is he to satisfy himself, at reasonable cost, that the material does conform to the requirements laid down? This necessitates the evolution of methods of test sufficiently well standardized to give consistent and dependable indications; for otherwise, poor material may at times be accepted or good material rejected unfairly.

Thus, while the primary work of the A.S.T.M. may be considered to be the formulation of specifications that make it possible to secure materials of known quality and assured suitability for specific uses, such specifications must be preceded by *research* and be followed by the evolution of a *method* or *methods of test*. With this prelude in mind there results, perhaps, a deepened appreciation of the clause used by the founders in stating the purpose for which the Society was organized. This clause is reproduced on page 343.

The Work of Standardization. The term "standard" refers to any of the results of the Society's standardizing activities and may apply to a specimen, to a method of test, or to definitions of terms.

Every A.S.T.M. standard is evolved and sponsored by a committee of specialists in the particular field of activity. The membership of the committee is divided about equally among persons identified with *consumer interests*, *producer interests*, and *general interests* (neutral). The Society in its standardization activities thus capitalizes upon the inherent diversity of interest between consumer and producer. The consumer group may be expected to stipulate requirements, and the producer group may be relied upon to detect items which are impracti-

cable and costly from the standpoint of manufacture. The general-interest group may be said to hold a balance of power and represents the judicial or disinterested contingent.

Since the adoption of a standard requires an almost unanimous committee approval, there is little reason to doubt that an A.S.T.M. standard or tentative standard represents the best that was known on the subject at the time of its adoption. Moreover, no standard is permanent. As the available knowledge or state of the industry changes, standards are revised, replaced, or abandoned. In an actively developing field, standards may undergo modification each year or two; other standards may continue for years without alteration.

The general-interest group is usually made up largely of the scientists and engineers connected with the research departments of government bureaus, state departments, and universities, and of independent consultants. This group supplies a large share of the backlog of research data so necessary for the standardizing activities, and so valuable for use in engineering design.

IMPORTANCE OF A.S.T.M. ACTIVITIES AND COOPERATION WITH OTHER AGENCIES

The A.S.T.M. is the leading organization of its kind in this country. The American Standards Association (A.S.A.), a federation of national associations and government departments, serves as a clearing house through which standardization programs can be coordinated. It has also set up procedures for approving standards submitted to it. Over 160 A.S.T.M. standards have been so approved by the A.S.A.

A.S.T.M. standards are to an ever-increasing extent written into government, city, state, and industrial specifications. Many other types of organizations carry on standardizing activity in fields not covered by the A.S.T.M. Among these are The Society of Automotive Engineers (S.A.E.), The American Railway Engineering Association (A.R.E.A.) and the Joint Committee on Specifications for Concrete and Reinforced Concrete. There is hearty cooperation between all such agencies and the A.S.T.M.

Membership. In the membership of the A.S.T.M. are represented most of the important industries of the country. The members can be roughly classified into three groups: (1) producers of raw materials and semifinished and finished products, (2) consumers of materials, and (3) a general-interest group, comprising engineers, scientists, educators, testing experts, research workers, etc. Membership is held by indi-

viduals, companies, associations, governmental departments, technical schools, and libraries.

There are four classes of active members: sustaining members, members, juniors, and students. The total membership at the time of writing this edition of this book was about 7,000. Probably there were about 500 student members at that time.

Publications of the A.S.T.M. The outstanding publications are (1) the *Book of A.S.T.M. Standards*, published triennially in several parts; (2) the *Proceedings* of the A.S.T.M., published annually and giving in one extensive volume the technical papers, reports of committees, and discussions and providing data on many engineering materials; (3) the *Bulletin* (10 issues yearly), with further technical papers and discussion.

In addition to these publications, occasional technical pamphlets too long for publication in the *Proceedings* or the *Bulletin* are issued. Separate copies of each A.S.T.M. Standard are also published. The accompanying list shows something of the extent of the ground covered by the 1949 A.S.T.M. "Book of Standards."

SPECIFICATIONS IN THE 1949 A.S.T.M. "BOOK OF STANDARDS"

Part	Classes of material	Approximate number of specifications
1.	Ferrous metals	245
2.	Nonferrous metals	201
3.	Cement, concrete, ceramics, thermal insulation, road materials, waterproofing, soils	319
4.	Paint, naval stores, wood, adhesives, paper, shipping containers	298
5.	Textiles, soap, fuels, petroleum aromatic hydrocarbons, water	311
6.	Electrical insulators, plastics, rubber	277

Scattered through the volumes are some 20 or 30 methods of testing and calibrating testing apparatus.

The Enforcement of Specifications, Factors and Principles Involved. These paragraphs on the enforcement of specifications are based on the 1907 A.S.T.M. presidential address which was given by the late Charles B. Dudley, the first president of the A.S.T.M.[1]

A specification is an attempt on the part of the consumer to tell the producer what he desires. In the early days of specifications, those attempts were crude. The consumer himself frequently knew little of the material that he attempted to describe or specify. The specification often took on the nature of an ultimatum by the consumer which the

[1] For the complete address see *Proc. A.S.T.M.*, Vol. 7, p. 19, 1907.

producer was apt to receive with antagonism. As the difficulty of formulating a wisely drawn specification came to be appreciated, the consumer consulted the producer in its preparation so that the specification has come to resemble a contract upon which minds have met and agreement has been reached.

The need for "enforcement" of specifications does not necessarily presuppose dishonesty or intentional evasion upon the part of the producer. Various factors enter into the problem, some of which will be mentioned. In the interest of brevity, materials that are "according to specifications" will be termed "satisfactory materials" and vice versa. The point of view is obviously that of the consumer.

1. When unsatisfactory materials are tendered it is often because of improperly worded specifications. In a contract there are often opportunities for two interpretations, each of which is justifiable.

Example. A lumberman bought logs under the simple specification that only two logs from each tree should be delivered. He received the small, knotty, tapering logs from the two top cuts. While the lumberman had in mind only the two "butt" cuts, the word "butt" had been omitted from the specification. Since a two-cut specification was unusual, and the price quite low, the producer was doubtless honest in his interpretation of the specification.

2. An unreasonable requirement may lead to evasion. Although a producer should not take a contract that he knows he cannot fill, he is placed in a somewhat delicate position if such a contract is offered. To remonstrate against the unreasonable requirement probably means the loss of a customer; to refuse the contract (as is often done) frequently makes an enemy of an otherwise competent engineer or expert. The producer, therefore, may take the contract with the expectation of getting along as best he may if difficulty does arise. He probably feels that he is making good material and giving good value and thus condones the breach of contract.

3. Unsatisfactory materials may result from the mistakes or misdeeds of subordinates.

Example. A railroad company contracted with a highly reputable firm for 50 barrels of the best grade of lard oil on a "rush" order. Tests showed the oil to be of a much inferior grade and it was promptly returned. The shippers made a barrel-to-barrel examination and found that only five barrels were of the inferior grade shown by the purchaser's test. The validity of the shipper's claim that only the five barrels should have been returned at their expense was denied by the railroad on the grounds that they had ordered only one grade of oil. Moreover, if the test sample had come from the satisfactory oil, the shippers would have profited from a clear case of fraud because of the difference in price of the two grades of oil. Still more important was

the question of safety since the oil was for use in signal lights and trainmen's lanterns, a purpose for which the inferior oil was utterly worthless.

The extent to which such mistakes occur with the knowledge and approval of superiors is not pertinent. They do occur and that fact is important in its bearing on the need for enforcement of specifications.

4. Commercial processes do not always yield what is expected of them.

Example. A shipment of phosphor-bronze bearing metal from a firm of the highest reputation showed no phosphorus, and rejection followed.

One of the principals of the firm stated that he had purchased phosphor-tin at a high price on a guarantee that it contained 10 per cent of phosphorus. He had overlooked the fact, however, that there was a loss of phosphorus every time the alloy was melted and that with careless foundry manipulation this loss might amount to all the phosphorus he had actually added. The firm modified its methods and subsequently made large quantities of acceptable material.

5. A contract taken at too low a figure may lead to unsatisfactory materials. Under stress of competition, agreements are made that, if carried out strictly in accordance with the specifications, would result in loss or lack of reasonable profit.

6. Manufacturers do not always know the characteristics of their products. If material is accepted without question, there is little incentive to perform tests and experiments to determine the exact properties of the material. Accordingly little or no knowledge regarding qualities that may be of the greatest interest to consumers is obtained. Often manufacturers reply to inquiries that they can produce according to a given specification if anyone can. Yet without definite knowledge, contracts are taken and shipments are made. After material has been tested and found unsatisfactory, the explanation is offered that although it does not quite meet the specifications it still is good material and will do the work. This is, of course, beside the question. If the consumer had been willing to use material that was "just as good" he would have changed his specification in order to obtain the corresponding variation in price.

7. Unforeseen difficulties such as an unexpected scarcity of raw materials may cause a manufacturer to proceed with available but inferior materials. He may make deliveries knowing that there may be trouble, and asks for leniency when the trouble arises. Savoring of a deliberate attempt to force the acceptance of material, regardless of quality, is the contention that delay must follow if unsatisfactory goods that have been tendered are not accepted. In all such cases the producer should make a frank statement of the situation in advance before such

a statement becomes an alibi to excuse accomplished performances or attempts.

The foregoing considerations show a need for enforcing specifications without necessarily assuming that producers are dishonest or that they do not intend to do as they have agreed. In fact the producer recognizes the importance of having adequate inspection of deliveries. The examination and testing of the material should be such that they shall leave no loopholes for evasion or substitution. The following points are essential to the accomplishment of this end:

1. In most cases only a small portion of the material, a sample, can be subjected to test. Certain principles must control the selection of the sample.

a. A representative of the consumer must take the sample.

b. The sample must be representative of the whole lot and should represent a definite amount of material. For materials that are produced in heats or stored in tanks or bins, one set of tests may cover the whole amount. In other cases one set of tests may be necessary for each delivery or shipment.

c. The sample must be taken at random. If the barrel nearest the car door, a sample from the top of the sack, or the axle from the top of the pile is always selected, rejections may become less frequent than they should.

d. The sampled material should not remain in the hands of the producer after it has been sampled. This rule is not always easy to follow. Materials that are sampled and tested after they arrive at destination present no difficulties. Materials that can be loaded at once may be inspected at the source. When storage is necessary between inspection and shipping, effective sealing or marking that cannot be effaced without easy detection should always be employed.

The question may be asked whether a sample taken with all known precautions actually represents the whole lot. If the specification has been intelligently drawn it will include permissible tolerances to allow for reasonable variations due to uncertainties in manufacture or unavoidable errors of manipulation. This leaves only intentional or unintentional variations to be provided against. It would appear that if the producer assumes the risk that the sample may come from an inferior portion of the material with the rejection that would inevitably follow, the consumer should risk getting a sample from a better portion with consequent acceptance of some inferior material.

2. If the sampling has been properly done and the material found unsatisfactory, prompt rejection should follow.

Testing was never intended to be a device to bring about the accept-

ance of inferior material, and accordingly, if the tests show that the material does not comply with specifications, the material should be rejected.

Uncertainty in the reliability of the tests is a different matter. If the producer can show reasonable grounds for reopening the case, the consumer should welcome retests and give him every facility for satisfying himself that no injustice has been done. It is good practice to keep a sample of all rejected material for a month and to give the producer half for verification if he wishes it. There should be nothing secret or arbitrary in sampling, testing, or rejecting material.

3. The use of rejected materials presents a difficult problem. Although admitting the failure, the producer may contend that the material is only slightly deficient and will give good service. In urging the consumer to accept rejected material, the producer is virtually requesting him to annul specifications which have been agreed to by both producer and consumer. Such procedure leads to a complete breakdown of specifications. On the other hand, if the producer offers to sell the rejected material to the consumer at a reasonable reduction in price, a new and proper basis for a legitimate business transaction is furnished. If the consumer can use the material at an equitable price, he may then purchase it under a new specification which the material can meet.

In view of the present knowledge of materials and methods of testing, the purchaser should not always feel that he can pass on to the producer the blame for loss of life and property due to faulty materials. It is a part of the responsibility of the purchaser to ascertain his needs, to specify them adequately, and to assure himself that the specifications have been met.

Two Typical A.S.T.M. Specifications. As illustrating typical specifications for metals and for nonmetals, A.S.T.M. specifications for carbon-steel bolting material and for load-bearing wall tile are offered. Students (or teachers) who wish to have available more specifications to study can find them in the pamphlet "Selected A.S.T.M. Standards for Students in Engineering." This pamphlet contains some three dozen typical standards, including those for ferrous metals, nonferrous metals, and nonmetals. The pamphlet may be obtained from the American Society for Testing Materials.

In connection with the study of standards for materials, the following concise statement should always be kept in mind: "The A.S.T.M. Standards are subject to revision from time to time. For information on latest revisions and for copies of specifications, contact A.S.T.M. Headquarters, 1916 Race Street, Philadelphia 3, Pa."

STANDARD SPECIFICATIONS FOR HEAT-TREATED CARBON-STEEL BOLTING MATERIAL[1]

(Courtesy of the American Society for Testing Materials)

A.S.T.M. Designation: A 261—47

ADOPTED, 1947[2]

This Standard of the American Society for Testing Materials is issued under the fixed designation A 261; the final number indicates the year of original adoption as standard or, in the case of revision, the year of last revision.

1. Scope. (*a*) These specifications cover heat-treated carbon-steel bolting material 2 in. and under in diameter for pressure vessels, valves, flanges, and fittings. The term "bolting material" as used in these specifications covers bars, headed bolts, screws, studs, and stud bolts.

(*b*) One grade of material is covered, designated grade BO.

(*c*) Nuts and washers for use with this bolting material are covered in Section 15.

2. Basis of Purchase. When agreed upon by the manufacturer and the purchaser, Brinell hardness tests may be made to determine the acceptance of bolting material in lieu of the tension tests prescribed in these specifications, but they shall not be used as a basis for rejection without confirming tension tests being made.

3. Processes. The steel shall be made by either or both of the following processes: open-hearth or electric-furnace.

4. Discard. A sufficient discard shall be made from each ingot to secure freedom from injurious piping and undue segregation.

5. Heat-treatment. (*a*) Heat-treatment shall consist of liquid quenching and tempering.

(*b*) After the last hot or cold forming operation, the bolting material shall be uniformly reheated from a temperature below the cooling critical range to the proper temperature to refine the grain (a group thus reheated being known as a "quenching charge"). The material shall then be quenched in some liquid medium under substantially uniform conditions for each quenching charge. The material shall then be uniformly reheated to at least 950°F. for tempering (a group thus reheated being known as a "tempering charge") and allowed to cool uniformly.

6. Chemical Composition. The steel shall conform to the following requirements as to chemical composition:

[1] Under the standardization procedure of the Society, these specifications are under the jurisdiction of the A.S.T.M. Committee A 1 on Steel.

[2] Prior to their adoption as standard, these specifications were published as tentative from 1943 to 1947, being revised in 1944.

In October, 1948, the word "physical" was changed editorially to "mechanical" and the word "melt" to "heat" throughout these specifications.

	Ladle analysis	Check analysis
Carbon, max., per cent	0.55	0.57
Manganese, max., per cent	1.00	1.06
Phosphorus, max., per cent	0.04	0.048
Sulfur, max., per cent	0.05	0.058
Silicon, min., per cent	0.15	0.13

7. Ladle Analysis. An analysis of each heat of steel shall be made by the manufacturer to determine the percentages of the elements specified in Section 6. This analysis shall be made from a test ingot taken during the pouring of the heat. The chemical composition thus determined shall be reported to the purchaser or his representative, and shall conform to the requirements for ladle analysis, specified in Section 6.

8. Check Analysis. An analysis may be made by the purchaser from samples representing the bolting material. The chemical composition thus determined shall conform to the requirements for check analysis specified in Section 6.

9. Tensile Properties. (*a*) The material after heat-treatment shall conform to the following requirements as to tensile properties at room temperature:

	Grade BO
Tensile strength, min., psi	100,000
Yield point, min., psi	75,000
Elongation in 2 in., min., per cent	16
Reduction of area, min., per cent	45

(*b*) The yield point shall be determined by the drop of the beam or halt in the gage of the testing machine, or by the use of dividers or other approved method, at a crosshead speed not to exceed ⅛ in. per min. The tensile strength shall be determined at a speed of head not to exceed 1½ in. per min.

10. Hardness Test. (*a*) When Brinell hardness tests are made, the boiling material, after final heat-treatment, shall have a Brinell hardness of 200 to 260.

(*b*) In making the Brinell hardness test, reference should be made to the Standard Method of Test for Brinell Hardness of Metallic Materials (A.S.T.M. Designation: E 10).[1]

11. Test Specimens. (*a*) The tension test specimens taken from bar stock, finished bolts, screws, studs, and stud bolts shall be machined to the form and dimensions shown in Fig. 140, except as specified in Paragraph (*b*).

(*b*) In the case of small sections which will not permit of taking the standard tension test specimen specified in Paragraph (*a*), the tension test specimen shall be as large as feasible and its dimensions shall be proportional to those shown in Fig. 140. The gage length for measuring elongation shall be four times the diameter of the specimen.[2]

[1] See 1949 Book of A.S.T.M. Standards, Part I, p. 1249.

[2] These requirements are in accordance with the provisions of Section 8 of the

(c) Specimens for tension tests shall be taken longitudinally. For sizes under 1½ in. in diameter, the full section shall be turned to conform to requirements specified in Paragraph (a). For sizes 1½ in. and larger, the specimen shall be taken halfway between the center and surface.

12. Number of Tests. (a) For bars, one tension test shall be made from each tempering charge. If more than one quenching charge is represented in a tempering charge, one tension test shall be made from each quenching charge. If more than one heat is represented in a quenching charge, one tension test shall be made from each heat.

(b) Except as specified in Paragraph (c), one tension test shall be made for each lot of 2,000 pieces or fraction thereof of bolts, screws, studs, and stud bolts

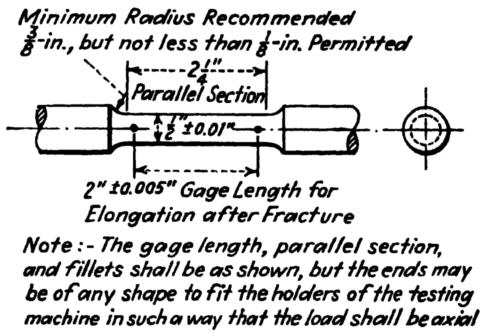

FIG. 140. Standard round test specimen with 2-in. gage length.

for sizes 1 in. and under in diameter; or for each lot of 1,000 pieces or fraction thereof for sizes over 1 in.

(c) Unless required on the order, tension tests shall not be made on an order of less quantity than specified in Paragraph (b); in which case acceptance shall be based upon the provisions in Section 18 (b).

(d) If any test specimen shows defective machining or develops flaws, it may be discarded and another specimen substituted.

(e) If the percentage of elongation of any tension test specimen is less than that prescribed in Section 9 (a) and any part of the fracture is more than ¾ in. from the center of the gage length, as indicated by scribe scratches marked on the specimen before testing, a retest shall be allowed.

(f) When Brinell hardness tests are made in lieu of tension tests at least four times the number of pieces shall be tested. See tentative revision after Section 20.

13. Retests. If the results of the mechanical tests of any test lot do not conform to the requirements specified, the manufacturer may retreat such lot not more than twice, in which case two additional tension tests shall be made from such lot, all of which shall conform to the requirements specified.

Standard Methods of Tension Testing of Metallic Materials (A.S.T.M. Designation: E 8), 1949 Book of A.S.T.M. Standards, Part I, p. 1234.

14. Finish. (*a*) Bolts, screws, studs, and stud bolts shall be pointed and shall have a workmanlike finish.

(*b*) Standard permissible variations for dimensions of bars shall be as set forth in the following table:

PERMISSIBLE VARIATIONS IN SIZE OF HOT-ROLLED BARS

Specified size, in.	Permissible variations from specified size, in.		Out-of-round, in.
	Over	Under	
5/16 and under	0.005	0.005	0.008
Over 5/16 to 7/16, incl	0.006	0.006	0.009
Over 7/16 to 5/8, incl	0.007	0.007	0.010
Over 5/8 to 7/8, incl	0.008	0.008	0.012
Over 7/8 to 1, incl	0.009	0.009	0.013
Over 1 to 1 1/8, incl	0.010	0.010	0.015
Over 1 1/8 to 1 1/4, incl	0.011	0.011	0.016
Over 1 1/4 to 1 3/8, incl	0.012	0.012	0.018
Over 1 3/8 to 1 1/2, incl	0.014	0.014	0.021
Over 1 1/2 to 2, incl	1/64	1/64	0.023

(*c*) Headed bolts shall be semifinished, hexagonal or square in shape, and in accordance with the dimensions for the regular or heavy series, as required, of the American Standard for Wrench-head Bolts and Nuts and Wrench Openings (ASA No. B18.2—1941). Unless otherwise specified, the American Standard heavy hexagon series shall be used.

15. Nuts and Washers. Bolts, studs, and stud bolts shall be equipped with nuts conforming to the Standard Specifications for Carbon- and Alloy-steel Nuts for Bolts for High-pressure and High-temperature. If washers are used under nuts they shall be of forged or rolled steel. All washers shall be free from injurious defects and shall have a workmanlike finish.

16. Threads. (*a*) All carbon-steel bolts, studs, and stud bolts, and accompanying nuts, unless otherwise specified, shall be threaded in accordance with the American War Standard for Straight Screw Threads for High-strength Bolting (ASA No. B14.—1945).

(*b*) Where practical, all threads shall be formed after heat-treatment.

17. Marking. The serial marking, BO, for identification of material and the manufacturer's identification mark shall be stamped on the top of the head of bolts and screws, and on one end of studs and stud bolts. The symbol BO will indicate that the material is carbon steel of the composition specified in Section 6.

18. Inspection. (*a*) The inspector representing the purchaser shall have free entry, at all times while work on the contract of the purchaser is being performed,

to all parts of the manufacturer's works that concern the manufacture of the material ordered. The manufacturer shall afford the inspector all reasonable facilities without charge, to satisfy him that the material is being furnished in accordance with these specifications. All tests (except check analysis) and inspection shall be made at the place of manufacture prior to shipment, unless otherwise specified, and shall be so conducted as not to interfere unnecessarily with the operation of the works.

(*b*) *Certification.*—When agreed upon in writing between the manufacturer and the purchaser, a certification that the material conforms to the requirements of these specifications shall be the basis of acceptance of the material. Otherwise, the manufacturer shall report to the purchaser or his representative the results of the chemical analyses and physical tests made in accordance with these specifications.

19. Rejection. (*a*) Unless otherwise specified, any rejection based on tests made in accordance with Section 8 shall be reported to the manufacturer within five working days from the receipt of samples by the purchaser.

(*b*) Material that shows injurious defects subsequent to its acceptance at the manufacturer's works will be rejected, and the manufacturer shall be notified.

20. Rehearing. Samples tested in accordance with Section 8 that represent rejected material shall be preserved for two weeks from the date of the test report. In case of dissatisfaction with the results of the test, the manufacturer may make claim for a rehearing within that time.

Tentative Revision, June, 1941

Section 12. Revise to read as follows:

12. (*a*) One tension test shall be made for each diameter of each heat represented in each tempering charge. In the continuous type treatment a charge shall be defined as 6,000 lb.

(*b*) For studs, bolts, screws, etc., one tension test shall be made for each diameter of each heat involved in the lot. Each lot shall consist of the following:

Diameter, in.	Lot size
1⅛ and under	1,500 lb. or fraction thereof
Over 1⅛ to 1¾, incl	4,500 lb. or fraction thereof
Over 1¾ to 2½, incl	6,000 lb. or fraction thereof
Over 2½	100 pieces or fraction thereof

(*c*) Tension tests are not required to be made on bolts, screws, studs, or stud bolts which are fabricated from heat-treated bars furnished in accordance with the requirements of these specifications and tested in accordance with Paragraph (*a*), provided they are not given a subsequent heat-treatment.

(*d*) When Brinell hardness tests are made in lieu of tension tests at least four times the number of pieces shall be tested.

STANDARD SPECIFICATIONS FOR STRUCTURAL CLAY LOAD-BEARING WALL TILE[1]

(*Courtesy of the American Society for Testing Materials*)

A.S.T.M. Designation: C 34—50

ADOPTED, 1936; REVISED, 1939, 1941, 1949, 1950[2]

This Standard of the American Society for Testing Materials is issued under the fixed designation C 34; the final number indicates the year of original adoption as standard or, in the case of revision, the year of last revision.

1. Scope. (*a*) These specifications cover structural clay load-bearing wall tile made from surface clay, shale, fire clay, or mixtures thereof. Two grades of tile are covered, as follows:

Grade LBX. Suitable for general use in masonry construction and adapted for use in masonry exposed to weathering, provided they are burned to the normal maturity of the clay. They may also be considered suitable for the direct application of stucco.

Grade LB. Suitable for general use in masonry where not exposed to frost action, or for use in exposed masonry where protected with a facing of 3 in. or more of stone, brick, terra cotta, or other masonry.

(*b*) If tile having a particular color, texture, or finish are desired, these features should be specified separately by the purchaser (see Explanatory Note 1).

2. Physical Properties. (*a*) Structural clay load-bearing wall tile shall conform to the requirements as to physical properties for the grade specified as prescribed in the following table:

PHYSICAL REQUIREMENTS

Grade	Maximum water absorption[a] by 1-hr. boiling, per cent		Minimum compressive strength (based on gross area),[b] psi.			
			End construction tile		Side construction tile	
	Average of five tests	Individual	Average of five tests	Individual	Average of five tests	Individual
LBX....	16	19	1400	1000	700	500
LB.....	25	28	1000	700	700	500

[a] The range in percentage absorption for tile delivered to any one job shall be not more than 12.

[b] Gross area of a unit shall be determined by multiplying the horizontal face dimension of the unit as placed in the wall by its thickness.

[1] Under the standardization procedure of the Society, these specifications are under the jurisdiction of the A.S.T.M. Committee C-15 on Manufactured Masonry Units.

[2] Prior to their present adoption as standard, these specifications were published as tentative from 1921 to 1926, being revised in 1924 and 1926. They were adopted in 1926, revised in 1927, 1930, and 1931, but withdrawn and replaced in 1934 by C 34–34 T which were published as tentative from 1933 to 1936, being revised in 1934, 1935, and 1936.

(*b*) Tile of grade LBX shall be accepted under all conditions in lieu of grade LB.

(*c*) End-construction tile are tile designed to be placed in the wall with axes of the cells vertical. Side-construction tile are tile designed to be placed in the wall with the axes of the cells horizontal. Where end-construction tile are used on the side they shall conform to the requirements of side-construction tile and *vice versa*.

(*d*) Bonding tile shall be so designed as to provide recesses for header brick courses when laid up in brick-faced walls.

3. Number of Cells. (*a*) Load-bearing tile shall conform to the following requirements as to minimum number of cells[a] in the direction of wall thickness (see Explanatory Note 2 for approximate weights of tile):

Nominal horizontal thickness of tile as laid in wall, in.	Minimum number of cells[a] in direction of wall thickness
4	1
6	2
8	2
10	2
12	3

[a] Cells are hollow spaces enclosed within the perimeter of the exterior shells, and having a minimum dimension of not less than ½ in. and a cross-sectional area of not less than 1 sq. in.

(*b*) In double-shell tile, the two voids between exterior and interior shells on the sides of the tile shall be considered as one cell in thickness of wall when their combined width is not less than ½ in., provided the short webs between the inner and outer shells are not greater in number or thickness than the long transverse webs holding the inner shells.

(*c*) Reentrant spaces not less than 1 in. in depth and not less than 1 sq. in. in area, which form cells when the units are laid in the walls, shall be considered as cells in the direction of wall thickness, but not in the units.

4. Shell and Web Thickness. (*a*) The average over-all thickness of the shells, measured between the inner and extreme outer surfaces of end-construction load-bearing tile, shall be not less than ¾ in., except that in double-shell tile the combined average over-all thickness of the inner and outer shell shall be not less than ¾ in. The thickness of the webs shall be not less than ½ in.

(*b*) The average over-all thickness of the shells, measured between the inner and extreme outer surfaces of side-construction load-bearing tile, shall be not less than ⅝ in., except that in double-shell tile the combined average over-all thickness of the inner and outer shell shall be not less than ¾ in. The thickness of the webs shall be not less than ½ in.

(*c*) The width of any cell in side-construction tile, measured in the direction of wall thickness, shall not exceed four and one-half times the average over-all thickness of either the upper or lower bearing shells. If no cell in side-construction tile, measured in the direction of the wall thickness, exceeds four times the average over-all thickness of either the upper or lower bearing shells, the requirements for minimum shell and web thickness specified in Paragraph (*b*) shall be waived.

(*d*) The thickness of bonding and other types of tile manufactured for use in combination with brick or other materials may vary from the nominal thicknesses indicated in Section 3, as required by construction requirements.

5. Permissible Variations in Dimensions. No over-all dimension shall vary more than 3 per cent over or under the specified dimension for any form or size of tile.

6. Finish. (*a*) The finish of the outer face or faces of tile shall be plaster-base finish or exposed wall finish as specified in the invitation for bids.

(*b*) Surfaces of tile for plaster-base finish shall be smooth, scored, combed, or roughened. When smooth, the tile shall be free of glaze and the absorption shall be not less than 5 per cent nor more than 25 per cent. When scored, each groove shall be not less than $\frac{1}{16}$ in. nor more than $\frac{1}{4}$ in. in depth, and not more than 1 in. in width. The area covered by the grooves shall not exceed 50 per cent of the area of the scored faces. When combed, the tile shall be scratched or scarified prior to burning by mechanical means which shall make scratches or scarifications on the surface of the tile not less than $\frac{1}{16}$ in. nor more than $\frac{1}{8}$ in. in depth, and not more than $\frac{1}{4}$ in. apart. When roughened, the die skin on the face of the tile shall be entirely broken by mechanical means, such as wire cutting or wire brushing. (The die skin may be observed within the cells of the tile.)

(*c*) Surfaces of tile with exposed finish shall be smooth, combed, or roughened. Combed or roughened tile surfaces shall conform to the requirements for these finishes given in Paragraph (*b*).

7. Marking. At least 80 per cent of each shipment of structural clay tile, as delivered to the site, shall bear the name, initials, trade-mark, or identification of the manufacturer. These marks shall be indented on the outside or inside of the tile and shall be easily identified.

8. Visual Inspection. (*a*) All tile shall be reasonably free from laminations and from cracks, blisters, surface roughness, and other defects that would interfere with the proper setting of the tile or impair the strength or permanence of the construction.

(*b*) When unscored (smooth) tile are specified, the requirements, except as to scoring, shall be the same as for scored tile. If closer tolerances on dimensions and on freedom from belt marks, chips, surface discolorations, and roughness are desired, such requirements shall be clearly defined in supplementary specifications.

9. Rejection. In case the shipment fails to conform to the requirements for the grade specified, the manufacturer may sort it, and new specimens shall be selected by the purchaser from the retained lot and tested at the expense of the manufacturer. In case the second set of specimens fails to meet the requirements, the entire lot shall be rejected.

10. Expense of Tests. Except as specified in Section 9, and unless otherwise agreed, the expense of inspection and testing shall be borne by the purchaser.

11. Sampling and Testing. (*a*) The purchaser or his authorized representative shall be accorded proper facilities for sampling and inspection of units both at the place of manufacture and at the site of the work. At least ten days from the time of sampling should be allowed for completion of the tests.

(*b*) Tile shall be sampled and tested in accordance with the Standard Methods of Sampling and Testing Structural Clay Tile (A.S.T.M. Designation: C 112) of the American Society for Testing Materials.

Explanatory Notes

NOTE 1. Color of tile varies with the type of clay used and degree of burning; hence, it cannot be taken as indicative of classification until after it has been related to absorption and strength by actual tests.

NOTE 2. The following average weights of structural clay load-bearing wall tile are given only as information:

Nominal horizontal thickness of tile as laid in wall, in.	Average weight, lb. per sq. ft. of tile[a]
4	20
6	30
8	36
10	42
12	52

[a] The weights given in the above table are for scored tile. If any of the faces are not scored, the weights are increased 1 lb. per sq. ft. of unscored area.

Tentative Revision, September, 1950

New Note. Add a new Note 3 to the Explanatory Notes to read as follows:

NOTE 3. Purchasers and designers should ascertain the type and size of tile available in the locality under consideration and should specify accordingly, stating the size and type represented by the available tile. Not all modular and nonmodular tile are produced in some parts of the United States.

Modular sizes are designated by nominal dimensions which are equal to the standard dimensions plus the thickness of one mortar joint, not to exceed ½ in. Standard dimensions of tile are the manufacturers' designated dimensions.

Comment on the Specifications for Load-bearing Wall Tile. In the specifications for structural clay load-bearing wall tile, the required compressive strength is based on the load per square inch of the *gross* cross-sectional area. Turning to Fig. 79, page 209, the gross cross section of the tile shown in the upper right hand of the figure is 64 sq. in. if the load is applied endwise, and 96 sq. in. if the load is applied sidewise. Now, if the loss of cross-sectional area due to the cells in the tile is taken out, and the cells in the tile are each 3 by 3 in. square, the *net* area of cross section to resist endwise load is $64 - (4 \times 3^2) = 28$ sq. in. The *net* cross section to resist sidewise load is $96 - (2 \times 3 \times 12) = 24$ sq. in. If the stress were computed on the basis of *net* cross section, for endwise load it would be $64/28 = 2.28$ times the value found for the stress computed on the basis of the *gross* area, and for sidewise load the corresponding factor is $96/24 = 4$.

Selected References for Further Study

1. American Society for Testing Materials, Philadelphia. "Standards," published every three years in two volumes (the current volumes were issued in 1955); "Selected Standards for Students," a small booklet containing a discussion of the principles of making standard specifications for materials and a number of representative specifications.
2. Standard specifications issued by
   American Railway Engineering Association
   Society of Automotive Engineers
   American Society for Metals (mostly methods of test)
   Master Car Builders' Association
   American Foundrymen's Association
   Southern Pine Association
   West Coast Lumbermen's Association
   National Lumber Manufacturers' Association
   American Concrete Institute
   U. S. Federal Specifications Board
3. American Standards Association. This body issues as "American Standards" specifications for materials, building practice, and safety devices which have been found to be acceptable to the various interests concerned with any specification.
4. Dudley: "The Enforcement of Specifications," *Proc. A.S.T.M.*, Vol. 7, p. 19, 1907.
5. A.S.T.M.: "The Economic Significance of Specifications for Materials," a symposium held June 25, 1931. Published by the Society.

Questions

1. Describe the procedure of the A.S.T.M. in formulating standard specifications for materials.

2. What is the difference between *tentative standards* and *standards* of the A.S.T.M.?

3. State at least four principles to be followed in sampling material.

4. Using the testing equipment in your laboratory, could you make acceptance tests of specimens of carbon steel for bolting material? Could you machine the standard test specimens for this test in your laboratory shop or would they have to be machined elsewhere? How many specimens would you wish to have for each lot of steel tested? In carrying out the strength tests of bolting material, how is the elastic strength determined? Does this method require delicate measurements of elongation? Do you think that this is a good test? Give your reasons.

5. Ten specimens from a lot of clay-load-bearing tile are tested. Five of them are tested in compression under endwise loading; the other five are tested under sidewise loading. The tiles are 12 in. long and 8 by 8 in. over-all cross section. In each tile there are four cells 3.25 in. wide by 3.25 in. deep. The five specimens tested under endwise load failed at 65,100, 63,400, 66,600, 64,000, and 63,800 lb. load, respectively. Would the tile be classified as grade LBX, grade LB, or would it be rejected as end-loaded tile? The other five tile were tested under sidewise loading and failed at 68,100, 66,500, 67,200, 67,900, and 66,600 lb. load, respectively. How would they be graded as tile for bearing sidewise loading?

6. Why are tension tests not used for acceptance tests for concrete for building blocks? Why are tension tests used for acceptance for metallic materials?

7. Compare results of tests of materials made in your laboratory course with the requirements of the A.S.T.M. standards, or if the latter are not available, with standards in local building ordinances, or by those of some U. S. Government department.

CHAPTER XX

STRESS, STRAIN, ATOMIC AND CRYSTALLINE DISTORTION, AND STRUCTURAL DAMAGE TO MACHINE PARTS AND STRUCTURAL MEMBERS

In the first chapter of this book there is a discussion of various factors which add to or subtract from the strength of a material. In this, the last chapter, it seems to the writers that a second brief general discussion of the strength of materials may be useful, now that the behavior of many of the engineering materials has been studied.

When a structural member or a machine part is fractured or distorted to such an extent that it can no longer function properly, it has suffered "structural damage" and it must be repaired or replaced. The common formulas of strength of materials, although not rigidly true for actual materials, are reasonably reliable, especially for parts under steady load. When using these common formulas, stress, strain, or strain energy is taken as a measure of the danger of structural damage. Most commonly *stress* is the measure used, although for nonbrittle materials *strain energy* seems slightly better. However, the various theories usually yield results not widely differing from each other, except when there are large *shearing* stresses, as is the case under torsional load.

These common formulas of mechanics of materials are based on four assumptions, three of which are plainly stated in most textbooks on mechanics of materials: (1) the material is homogeneous, (2) the material is isotropic (equally stretchable or compressible in all directions), and (3) Hooke's law (stress proportional to strain) holds. The fourth assumption, not often stated, but actually made, is (4) when at any *point* stress (or strain or strain energy) exceeds the stress for failure found in tests of specimens, then *the whole machine part or structural member has failed.*

None of these assumptions is rigidly true for the common structural materials—metals, wood, concrete, stone, and ceramic materials. (Some plastics seem to approach homogeneous structure quite closely.) Under the microscope metals are seen to be distinctly nonhomogeneous in their crystalline grains, and the nonhomogeneity of wood, stone, concrete, and ceramic materials is even more evident. Even metals are rarely, if ever, quite isotropic; wood is distinctly nonisotropic. Hooke's law is a very close approximation up to some limiting stress, but the stress of the first deviation from the straight-line proportionality is

dependent on the sensitivity of strain gage used, uniformity of stress in the test specimen, and scale used in plotting the stress-strain diagram.[1]

The first three assumptions seem to indicate that the computed stresses used are on the danger side. However, under a single application of stress the maximum stress would act on a "point" (actually over a very small area) and structural damage would not be done to the part *as a whole.* (Note that this is for a single application of stress.) The errors in the assumptions made in common formulas tend to neutralize each other, at least under steady load; an appreciable volume of material must be distorted or cracked before appreciable structural damage is done to a structural or machine member. However, in the case of a brittle metal a much smaller volume of overstressed metal will start a crack which will spread to fracture under a single load, than is the case with a part made of a ductile metal.

When we consider structural and machine parts under cycles of repeated stress (fatigue), structural damage by spreading cracks often occurs under computed stress much less than the stress for fracture under a single load, and sometimes under computed stress less than the yield strength of the metal. Under repeated stress the damaged "point" spreads and becomes an appreciable volume of damaged metal, until the strength of the whole structural or machine part is exceeded and fracture takes place, sometimes rather suddenly.

Fatigue tests of specimens of various metals have for most of the ferrous metals, and for some of the nonferrous metals, enabled the testing engineer to determine a stress range in a cycle of stress which can be repeated an indefinitely large number of times without fracture (see Chap. V for illustrations of this "endurance limit" or "fatigue limit," as it is called). In some tests, specimens have been subjected to hundreds of millions of stress cycles without fracture of the specimen, but on examining the specimens after testing a number of small cracks were found in the unfractured specimen. Evidently under repeated stress some cracks may start, spread a short distance (possibly into a region of lower computed stress), and then cease to spread further.

It has been found that the number of cycles with a given stress range which is required to cause fracture of a specimen or of a machine or structural part cannot be predicted with any satisfactory degree of reliability. In tests with sets of 20 specimens of the same size, shape, and material, and subjected to the same range of stress in a cycle, the number of cycles of stress for fracture varied from one to four times the minimum required for causing fracture (see Fig. 34, Chap. V). These

[1] See paper by R. L. Templin and discussion in *Proc. A.S.T.M.*, Vol. 29, Part II, 1929, pp. 523–553.

were steel specimens, and the range of "life span" for certain nonferrous metals has been found to be even greater.

To the writers the simplest explanation of the great variation of life span of a specimen under repeated cycles of the same stress range is the great variation in the actual path it may take as it spreads through millions of space-lattices of atoms and through thousands of crystalline grains with varying strength and of orientation of the atomic planes on which slip followed by fracture may start. The crack must pass through many "road blocks" of atom patterns and of the varying strength and orientation of the successive crystalline grains as it splits its way through the metal. The particular number and difficulty of the "road blocks" cannot be predicted in advance; at least no way to make such a prediction has yet been found. However, a crack usually starts in a region of high computed stress (tensile or shear stress) and, as it spreads, usually extends into regions of lower computed stress.

At the present time there are no formulas or diagrams by which to estimate quantitatively the effective strength of atomic bonds or of the crystalline structure of a metal. The best that can be done is to test specimens of the metal, or better yet to make tests of full-size structural or machine parts, and to determine the elastic strength and the fracture strength under static and repeated loading. Such "strength values" will then be a *statistical average* of the combined strengths of millions of atomic bonds acting at random in many directions. The problems of distortion and fracture due to "creep" of metals under steady load above certain temperatures (see Chap. IV) are somewhat similar to the problem of fracture of metals under cycles of repeated stress. However, in creep tests distortions and cracks develop more slowly, and *time* is the measure of life span rather than numbers of cycles of stress. The behavior of metals under simultaneous creep and repeated stress is briefly discussed in Chap. V.

Today the importance of further knowledge about the spread of cracks and about the part which the atomic structure and the crystalline structure of a metal play is very obvious. Every engineer who has to do with problems of strength of materials should try to keep in touch with the work of the metallurgist and of the atomic physicist, to whom we look hopefully for help in solving this problem of spreading fracture under repeated stress or under creep. Meanwhile, it would be well to continue to use a "factor of safety" (better called a "factor of uncertainty") when structures and machines are designed. Moreover, it must be expected that inevitably there will continue to be an occasional case in which failure occurs in spite of the best efforts of engineers to forestall it.

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